Journal of Transportation Technologies, 2024, 14, 195-211
https://www.scirp.org/journal/jtts
ISSN Online: 2160-0481
ISSN Print: 2160-0473

Intermodal Competition: Cargo Airships versus Long-Haul Trucking for Perishable Commodities

Barry Everett Prentice

Transport Institute, I.H. Asper School of Business, University of Manitoba, Winnipeg, Manitoba, Canada
Email: barry.prentice@umanitoba.ca

How to cite this paper: Prentice, B.E. (2024) Intermodal Competition: Cargo Airships versus Long-Haul Trucking for Perishable Commodities. *Journal of Transportation Technologies*, **14**, 195-211.
https://doi.org/10.4236/jtts.2024.142012

Received: February 2, 2024
Accepted: April 4, 2024
Published: April 7, 2024

Abstract

Intermodal competition changes with changes in technology, economics, and environmental concerns. Trucks and airships are generally considered not to be competitors, but this depends on the distance of haul. The tonne-kilometer cost of trucking rises much more quickly with distance than it does the cost of a cargo airship. At some distance, the two modes are direct substitutes. The costs of the Mexico-Canada refrigerated truck supply chain are compared with the costs of a 100t-lift, electrically-powered airship. The flight characteristics of the Hindenburg Zeppelin are used as a model for a modern cargo airship. The supply chain cost of trucking tomatoes is used to test the theorical proposition. The cost difference works out to about US10¢/kg (5¢/lb) advantage for trucking Mexican tomatoes to Canada. However, this cost disadvantage of the airship could be made up by their vibrationless ride, better air circulation and one-day service versus four days by truck. This alternative form of transportation could have a positive impact on worldwide north-south distribution of food. Airships can overcome trade barriers and distance to open new markets for perishable food exports. In addition, they would reduce the carbon emissions of transport. Canada imports 160,000 refrigerated truckloads of fruits and vegetables by from the southern US and Mexico. With an average driving distance of 3,000 km, these trucks emit 606,000 MT of CO_2 annually. Airships powered by hydrogen fuel cells would have zero-carbon emissions. Markets are not yet incorporating the environmental advantage of airships in any freight comparison, but inevitably this will be important.

Keywords

Airship, Refrigerated Trucks, Mexico, Tomatoes, Carbon-emissions, Perishables

1. Introduction

Transportation innovations can disrupt established markets and initiate a series of unforeseen changes. Large rigid airships flew across the Atlantic Ocean over 100 years ago but were abandoned following the invention of jet airplanes. With new materials and better methods, rigid airships are staging a comeback. Investments have been flowing into airship companies, like FLYING WHALES in France, Hybrid Air Vehicles in England and LTA Research in the United States [1]. A zero-carbon emissions cargo airship is likely to be commercially available within the next five years. Advances in airship technology could disrupt international trade where the only alternatives are ships and airplanes.

The demand for greener supply chains is providing impetus for airship developments. The uncertainty that still prevails in airship circles is where these aircraft will compete. The ability of airships to replace cargo jets on ocean routes is an obvious case [2], but a general assumption is that cargo airships cannot compete with the cost of trucks on overland routes. Certainly, this is true for short hauls, but for long hauls, trucks are not as competitive. Neal and Tay [3] posit that cargo airships should be most competitive with refrigerated trucks in the transport of perishable commodities. Airships should also have an environmental advantage. Refrigerated trucks are the most expensive (and polluting) surface transport vehicles moving long distances. This article examines whether a cargo airship of 100t lift capacity could compete with refrigerated trucks for distances over 3000 km.

No modern airships exist yet, but it is possible to test the proposition that a large airship could compete with trucks on a direct cost and environmental basis. The tools are historical records, market prices and technical proxies. Refrigerated truck freight and supply chain costs for perishable commodities are available to compare with future cargo airships. Tomatoes are the example cargo used in this analysis for the movement of fresh fruits and vegetables from Mexico to Canada. Estimates are easily be made of the carbon emissions of refrigerated trucks that could be saved by using electrically-propelled cargo airships.

The next section presents an economic framework to assess intermodal competition between trucks and airships. This framework is used to compare the direct and indirect costs of refrigerated tractor-trailers versus a Zeppelin-sized, rigid cargo airship. The literature on carbon footprints of food supply chains is reviewed to estimate the environmental impact of trucking of fresh fruits and vegetables. Subsequently, a cost analysis, using tomatoes as a representative cargo, is developed to examine the hypothesis that cargo airships can compete with long-haul trucking. The airship costs are based on historic data from the *Hindenburg*, and current aviation operations. In the penultimate section, non-monetary issues are considered including carbon emissions, customer service, phytosanitary barriers, and trade expansion. The paper concludes that new generation of cargo airships can compete with long-haul trucking, and that this alternative form of transport could alter world food distribution patterns.

2. Theoretical Framework for Intermodal Competition

Few technical hurdles must be overcome for cargo airships to compete with refrigerated trucks, but size is important. As an historical analogy, the railways could not compete with the cost of horse-drawn wagons, until their locomotives could haul more than five wagon-loads of freight [4]. Once the technical hurdles were overcome, trains became the dominant mode for long-haul freight movements[1]. Over the past 85 years, since the end of the large rigid airships, aviation technology has experienced rapid advances in materials and methods. Virtually everything needed to build a modern airship can be sourced from existing aviation supply chains. No one can predict the size of the new generation of rigid airships. The largest airships of the 1930s were 245 meters long and displaced 200,000 cubic meters, giving it a total lift of 200 metric tons (t).

The economies of size for airships follow the "square-cube rule" for buoyant vehicles. For a proportional increase in size, the surface area of the vehicle changes in proportion to the square of the length, while the volume increases by its cube. Like ships of the ocean, doubling the length of an airship results in eight times its original volume, which rapidly decreases the unit costs of moving cargo. The LRATC for airships in **Figure 1** is illustrated as falling rapidly as these vehicles get larger.

The economies of size for tractor-trailers are limited by the road infrastructure and highway regulations. In the case of the US Interstate highway system, trucks are limited to a gross vehicle weight of 80,000 pounds and 53-foot-long trailers. Trucks can gain efficiency by pulling more than one trailer, but this is not common for refrigerated trucks. In **Figure 1**, the Long Run Average Total Cost (LRATC) of trucking is represented by constant returns to scale. The competitive point is where the LRATC for airships and refrigerated trucks cross. This is denoted as Z. Airships larger than Z, would be competitive with the costs of trucking, depending on the distance.

Economies of distance and negative externalities contribute to intermodal competition advantages. **Figure 2** presents a comparison of cost based on distance travelled. Trucks are relatively inexpensive to lease, and most of their costs are

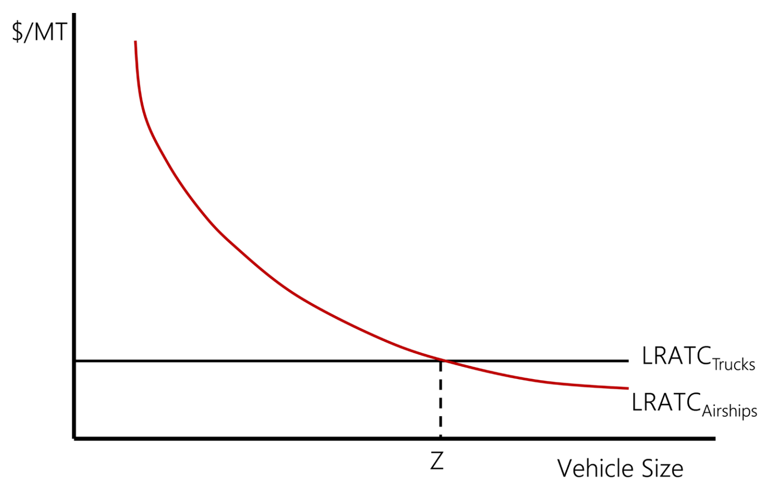

Figure 1. Intermodal competition: economies of vehicle size.

[1]The technical problem was the strength of the rails. The invention of puddling iron allowed engines and cars to become larger.

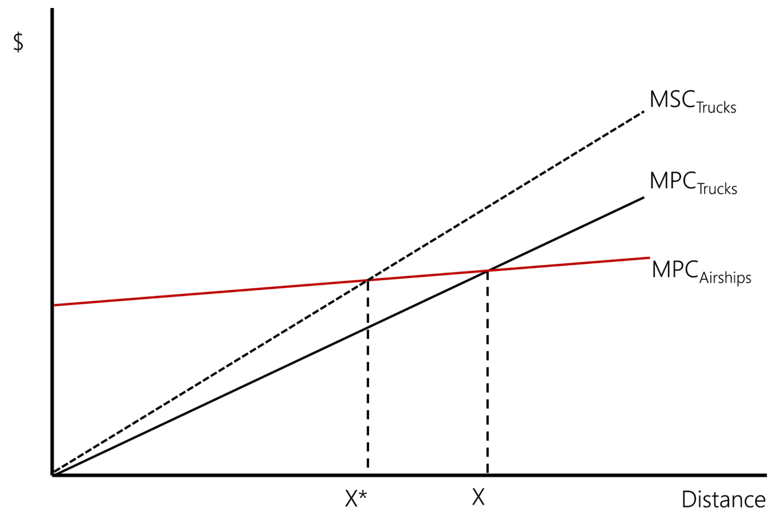

Figure 2. Intermodal competition: economies of distance.

variable, so the Marginal Private Costs of trucks (MPC_{Truck}) can be illustrated as a linear function of distance. Cargo airships have a much higher proportion of fixed costs to variable costs. The $MPC_{Airship}$ starts much higher but has a more gradual slope because the unit cost per kilometer is lower. The distance at which the cost of the airship ($MPC_{Airship}$) equals the cost of trucking (MPC_{Truck}) is denoted by X. For distances less than X, trucks would out-compete cargo airships and vice versa.

Negative externalities, such as GHG emissions, do not enter directly into the analysis of intermodal competition. These costs are borne by society in general, rather than by the carriers. The Marginal Social Cost (MSC_{Truck}) of trucking carbon emissions is represented by the sum of MPC_{Truck}. This represents the sum of their private costs plus their negative externality. Electrically-powered airships (using hydrogen fuel cells) would have no carbon emissions (the $MPC_{Airships}$ and $MSC_{Airships}$ are the same). If a monetary value were put on GHG emissions, the distance of intermodal competition would shift left to X*.

This comparison only considers the direct carbon emissions of these two transportation modes. Further research could calculate the life-cycle emissions from vehicle manufacture to disposal. Also, the carbon emissions involved in the production and distribution of their fuels (diesel versus hydrogen) could be included. A more comprehensive analysis of all possible carbon emissions would become more relevant if refrigerated tractor-trailers were electrically-powered, too. This analysis only considers carbon emissions from the combustion of fuel used in transport.

The impact of transport speed on intermodal competition is directly related to its effect on vehicle utilization. Transport output equals the number of trips (cycles) per year times the volume of freight carried. Airships are relatively slow for aircraft at 150 kilometers per hour (150 kmph). It would take approximately two days to make a round-trip from Mexico to Canada. For a cargo airship to generate enough productivity to compete over a 3000 km distance with trucks, they would have to be at least as large as the Zeppelins of the 1930 s.

Intermodal competition can also be affected by differences in transportation quality, such as travel time, extent of shipping damage (e.g., bruising), level of reliability and capacity (awkward configurations, low density, etc.). Transport vehicle capacity is often constrained by cargo volume, rather than weight. Fresh produce needs to be loaded so that air can circulate and avoid the buildup of carbon dioxide. Density is also a problem for some perishables. Shipments of head lettuce or spinach may only reach half the truck's weight limit before the trailer is deemed to be full[2]. For this analysis, all trucks and airships are assumed to be fully utilized in both directions.

Negative externalities do not enter into financial calculations of intermodal competition, at least not yet. Several countries, including Canada, have begun to impose carbon taxes on the sale of fossil fuels, but most of the route crosses Mexico and the US which do not put a price on carbon emissions. Nonetheless, it is important to acknowledge the volume of carbon emissions associated with the transport of food, often referred to as the carbon footprint.

3. Measuring Carbon Footprints

Carbon footprints for food supply chains have attracted both academic and general interest. The "100-Mile Diet" is a manifestation of the popular attention. Smith and MacKinnon [5] recount their experience of consuming only locally available food for a year. Their book tapped into the locavore movement that began as a desire to consume fresher, more nutritious food and to support local producers and farmers markets. Logic suggests that buying locally should reduce food prices and be more sustainable. Shorter travel distances mean lower transportation costs and less carbon emissions. As environmentalists embraced this idea, attention became focused on measuring the total carbon emissions resulting from food production and transportation.

Measurement of food supply chains' carbon footprints has generated considerable literature. In general, the research has not supported the perceived environmental benefit of a "100-Mile" Diet. Weber and Matthews [6] used an input–output life-cycle assessment to test the question of "food-miles" and transportation. "The results of this analysis show that for the average American household, "buying local" could achieve, at maximum, around a 4% - 5% reduction in [Greenhouse Gas] GHG emissions due to large sources of both CO_2 and non-CO_2 emissions in the production of food."

Wakeland *et al.* [7] examined carbon emissions of the food supply chain from the point of production to retail. They conclude that transport is not the most important part of the carbon footprint, despite the long distances that food may travel. This was followed by Poore and Nemecek [8] who undertook a meta-analysis. They reviewed 1530 studies, of which 570 were included, and supple-

[2]The density of cucumbers is 641 kilograms per cubic meter (kg/m^3), the density of tomatoes is 481 kg/m^3, lettuce is 368 kg/m^{3}and spinach is 168 kg/m^3. Data sourced from Machine and Process Design at http://www.mpd-inc.com/bulk-density/

mental data were added from 139 authors. The Greenhouse Gas (GHG) emissions for individual food products were estimated for each level of the supply chain.

Ritchie [9] employs the data collected by Poore and Nemecek [8] to create an accessible summary of their results. Table 1 presents a selection of these data for various major food categories in order of their total carbon footprint[3]. Livestock products are the largest contributors of GHGs, with field crops and orchards the lowest. The production-based GHG emissions for livestock and poultry overwhelm the share attributed to transportation.

The consensus of the literature is that the GHG impact of food transport does not support more local consumption as an environmental strategy. The exception is the transport of fresh fruits and vegetables. In the northern latitudes, fresh produce is only available locally in the summer season. During the other nine months of the year, non-storable fruits and vegetables travel long distances from sub-tropical and tropical regions.

Data provided by Ritchie [9] is re-arranged in Figure 3 to rank selected food

Table 1. Contributions to carbon footprint of the food supply chain.

	Land use	Animal						
Food product	Change	Feed	Farm	Processing	Transport	Packging	Retail	Total
(Kg of CO_2 emissions per Kg of food production)								
Beef (beef herd)	16.3	1.9	39.4	1.3	0.3	0.2	0.2	59.6
Lamb & Mutton	0.5	2.4	19.5	1.1	0.5	0.3	0.2	24.5
Cheese	4.5	2.3	13.1	0.7	0.1	0.2	0.3	21.2
Beef (dairy herd)	0.9	2.5	15.7	1.1	0.4	0.3	0.2	21.1
Pig Meat	1.5	2.9	1.7	0.3	0.3	0.3	0.2	7.2
Poultry Meat	2.5	1.8	0.7	0.4	0.3	0.2	0.2	6.1
Fish (farmed)	0.5	0.8	3.6	0	0.1	0.1	0	5.1
Eggs	0.7	2.2	1.3	0	0.1	0.2	0	4.5
Tofu	1	0	0.5	0.8	0.2	0.2	0.3	3
Milk	0.5	0.2	1.5	0.1	0.1	0.1	0.3	2.8
Tomatoes	0.4	0	0.7	0	0.2	0.1	0	1.4
Peas	0	0	0.7	0	0.1	0	0	0.8
Bananas	0	0	0.3	0.1	0.3	0.1	0	0.8
Brassicas	0	0	0.3	0	0.1	0	0	0.4
Potatoes	0	0	0.2	0	0.1	0	0	0.3
Apples	0	0	0.2	0	0.1	0	0	0.3
Citrus Fruit	−0.1	0	0.3	0	0.1	0	0	0.3

Source: Adapted from Ritchie (2020) Our World in Data.

[3]These data should be interpreted with care. They are more likely represent a cardinal ranking of the carbon footprints for different food supply chains, rather than a precise estimate of their differences.

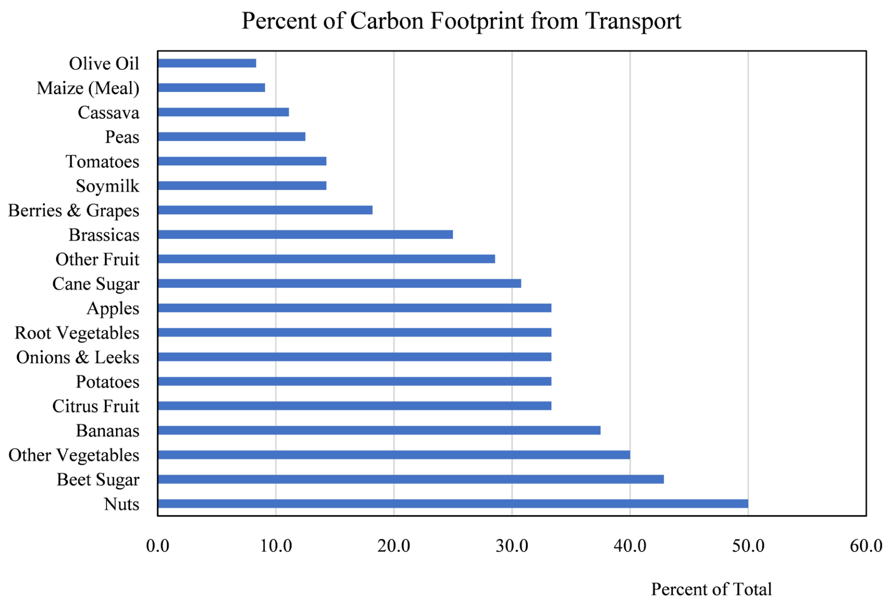

Figure 3. Ranking of food products by transportation GHG emissions.

products by the percentage of total GHG emissions contributed by transportation. These data show the size of the carbon footprint for the transport of selected fruits and vegetables. Transport's share can range from 15% to 40% of the total. A sustainability strategy for fresh produce is to shop locally when the season allows, and to use the means of transport with the lowest GHG emissions to obtain out-of-season produce.

The GHG emissions from transporting fresh produce by truck to Canada are likely much higher than the estimates in Figure 3. The average travel distance from the various North American production zones to Canadian cities is about 3000 kilometers. Diesel fuel consumption for a refrigerated tractor trailer is about 39.5 litres per 100 kilometers (L/100 km), thereby consuming about 1185 L of fuel to drive a 3000 km distance. The refrigeration system of the trailer (reefer unit) is estimated to consume 250 L of diesel fuel for the journey, increasing total fuel consumption to 1435 L (one-way). The carbon emissions from each liter of diesel fuel are 2.64 kilograms (kg) of CO_2[4]. Therefore each reefer trucks would release 3.8 t of CO_2 on the northbound trip. The round-trip would be double, but another commodity would be responsible for these emissions.

Canada imports 48.3% of all fresh fruits by refrigerated trucks from the southern US and Mexico. In 2021, these fresh fruit imports were valued at $4.0 billion and weighed 1.4 million t (metric tons) [10]. In 2020, 88.1% of all fresh vegetable imports to Canada were from the US and Mexico, too. They were valued at $3.1 billion and weighed approximately 1.6 million t [11].

The combined total of fresh fruit and vegetable imports from growing areas in the southern USA and Mexico weigh 3.0 million t. Using optimized lightweight

[4]Each litre of diesel fuel contains 720 grams of carbon and when burned produces 2640 grams of carbon dioxide.
https://connectedfleet.michelin.com/blog/calculate-co2-emissions/#:~:text=One%20litre%20of%20diesel%20creates,has%20emitted%20in%20a%20month.

trailers, the loads carried by refrigerated trucks are 42,500 to 44,000 pounds, which is 20,000 kg or 20 t. Therefore, about 150,000 truck-trailer shipments of fruit and vegetable are imported to Canada from the USA and Mexico. At 3.8 t of CO_2 per truck, for annual total emissions of 150,000 trucks would be approximately 570,000 t of CO_2.

4. Mexico-Canada Tomato Study

Trucking fresh produce from Mexico and the USA along selected transportation corridors to Canada could be replaced by zero-carbon emission, electrically-powered, cargo airships. Neal and Koo [3] found that a proposed cargo airship in Australia could capture up to 34% of the perishable food transport based on a shipper modal choice experiment. [12] Prentice *et al.* (2005) found that a rigid airship carrying pineapples and passengers could be competitive with ocean service, once established. This presents compares the costs of transporting fresh vegetables by cargo airships and refrigerated tractor-trailers.

Tomatoes are the largest volume of perishable vegetables imported from Mexico to Canada. A study on the shipment of tomatoes from Aguascalientes, Mexico to Winnipeg, Manitoba by Gonzalez [13] provides data to test the hypothesis that cargo airships can compete with refrigerated trucks. The supply chain costs for tomatoes provide representative freight rates because they are transported in full truckloads on a year-round basis. The consumption of tomatoes is sufficient to enable shipments of 100 t, or more, to be delivered to Winnipeg by cargo airships without flooding the market.

The supply chains for tomatoes are well-established and competitive. Winnipeg, Manitoba is almost equally far from all sources of production. **Figure 4** provides a map with distances from the production sources of tomatoes in the US and Mexico, as well as the greenhouse production areas in Ontario and British Columbia. The distances are slightly longer from Mexico, and the US-Mexico border crossing adds both time and cost to tomato shipments from Mexico. Mexican trucks are prohibited from crossing the US and must be unloaded at a US-Mexican border warehouse. This takes a minimum of one day, but shippers who were interviewed suggest that a delay of two to four days is quite common.

The State of Aguascalientes in central Mexico is the starting point of a 3500 km road journey that ends at Winnipeg, Manitoba. The tomatoes would be sent to the Reynosa, Mexico-McAllen, Texas border crossing where a major distribution centre is located. The refrigerated trailer is unhooked on the Mexican side of the border, pulled across by a drayage tractor and unloaded at a distribution warehouse at McAllen, Texas. US Customs processes the shipments, and from there the tomatoes are loaded into an American or Canadian truck and sent north via the Interstates I-35 and I-29 to Winnipeg, Canada.

Conceptual models of the supply chains for trucking and the proposed airship are presented in **Figure 5**. A truckload of tomatoes takes from four to eight days to make this trip. One day is for the movement to the U.S. border. A second day is spent crossing the border and unloading at a warehouse. Two more days are used to load and drive the truck across the USA to Winnipeg, Canada. This travel time and could be extended by the need for driver rest to meet hours of work regulations, diesel fill-ups, hygienic cleaning of food trailers, stops for temperature monitoring, traffic congestion, etc. The cargo airship would pick up the tomatoes close to the packing sheds and fly directly to a food distribution

Source: https://ontheworldmap.com/copyright/ with road distances from Google Maps

Figure 4. Travel distances in kilometers from tomato production zones to Winnipeg, Canada.

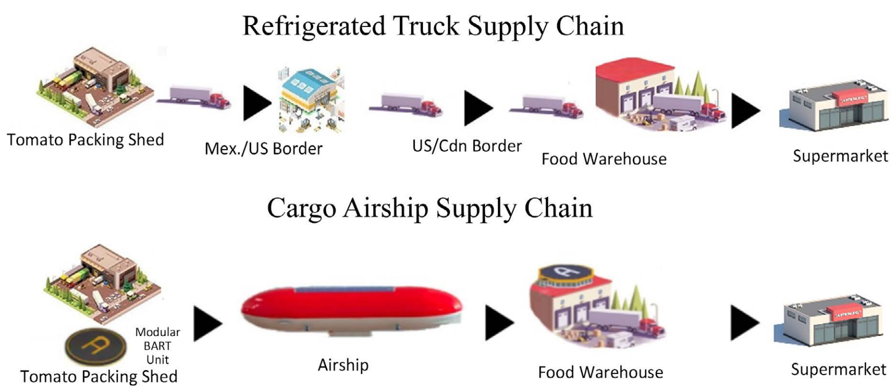

Figure 5. Truck and airship supply chains from Mexico to Canada for tomatoes.

warehouse for final distribution.

A summary of the trucking costs is presented in **Table 2**. These cost elements include Mexican trucking, custom inspections (US and Mexican), drayage charge to cross the border, and US or Canadian trucking charge to cross the US into Canada. Based on data collected in February 2020, the total cost for a single 20 t shipment would be US$11,867. For a 3500-kilometer trip, the cost per tonne-kilometer (t-km) is US$0.17 per t-km, or approximately US59¢ per kg.

4.1. Cargo Airship Cost Comparison

Insufficient data exists to estimate the economies of size for rigid airships in the 21st century. However, it is possible is to estimate the costs for one particular size of rigid airship using actual operating data, albeit based on 85-year-old Zeppelin technology.

The last rigid airships were the German Zeppelins that flew until 1939. The ill-fated, but highly successful *Hindenburg*, which operated over the Atlantic Ocean distances greater than 3000 km, is used as a model to develop a cost comparison for trucking[5]. The operating details of the *Hindenburg* are available online [14] and can be used to estimate the t-km costs for a similar-sized cargo airship. The *Hindenburg* was 245 metres long and 41 metres in diameter, with a hydrogen lifting gas capacity of 200,000 cubic meters. This provided a gross lift of 200 t. Rigid airships were roughly 50% dead-weight, which leaves 100 t for cargo. With 21st century materials and methods this could be further improved, but for this analysis a 100-t payload is used.

The historic data list the airship's cruising speed at 135 kmph. At this velocity, each of its four diesel engines consumed 180 kg/hr. Given the density of diesel fuel is 0.82 kg/L, this would result in an estimated total fuel consumption of about 875 L/hr. Some improvements in power plant efficiency and airship structures might allow for higher speeds and lower fuel consumption, but these original specifications are used here. **Figure 6** presents these data along with other important operating and input cost assumptions.

Table 2. Refrigerated truckload logistics costs for shipment from Mexico to Canada, 2020.

Logistics Costs from Aguascalientes Mexico to Winnpeg, Canada	
Trucking: Aguascalientes, Ags.- Reynosa, Tamaulipas	$2,149
Aduana Reynosa-McAllen Mexican Customs	$81
Trucking: Drayage of trailer at border crossing	$236
Aduana Reynosa-McAllen U.S. Customs	$122
Trucking: McAllen-Winnipeg	$9,279
Total Logistics Costs	$11,867
Cost per kilogram	$0.59
Source: Adapted from Gonzalez Alba, Marcela. (2021)	

[5]New York to Germany is over 5000 km versus 3000 km for this analysis.

Operating Assumptions	Input Cost Assumptions
Cruising speed – 135 kmph (80 mph)	Insurance - $5 million/year
Cargo capacity – 100 MT payload	Crew wages and benefits - $100,000/year/person
Useful operating life – 25 years	Fuel cost - $1/litre
Annual utilization – 330 days/year	Maintenance & Inspection costs - $1 million/year
Daily flying time – 20 hours/day	Ground handling costs- $1 million/year
Fuel consumption – 875 litres/hour	Airship purchase price - $100 million
Loading/unloading time – 2 hours	
Cargo utilization – 100 percent	**Output Productivity Assumption**
Crew size – 3/ship, 3 crews in rotation	89.1 million tonne-kilometers (MT-km)/year

Figure 6. 100-t cargo airship assumptions of operations, input costs and annual output.

For the long-distance transport of perishables, the airship is assumed to operate 330 days per year. This leaves 10% of its time for inspections, maintenance, and idle periods because of adverse weather. The daily flying time to Canada is set at 20 hours, with 2 hours at each end for loading and unloading. This allows the airship to complete one roundtrip every two days. With a payload of 100 t, traveling at 135 kmph, for 6600 hours per year, the airship produces 89.1 million tonne-kilometers of output annually.

Input cost assumptions are more difficult to compare with the *Hindenburg* because much has changed. The crew size on the *Hindenburg* was 39 (29 in operations and 10 in hospitality). This would be neither economic, nor necessary in 2024. With the use of computers, actuators, and many other technical advances the crew could be reduced to three people operating in rotation. This would leave one person always on duty to monitor systems and the automatic pilot. Airships provide lots of space for crew members to sleep on board. With the advances in drone technology, it is unclear that any crew members will be on-board a future airship, although a ground-based pilot will still be on duty.

A key assumption in this comparison is that a hydrogen fuel cell power system would consume about the same value of energy as the diesel engines of the *Hindenburg*. This depends on the efficiency of a hydrogen fuel cell power system and the cost of hydrogen. Lof, *et al.* [15] provide a comparison of hydrogen fuel cell electric (HFCE) tractor-trailers versus diesel fuel internal combustion engines (ICE) tractor-trailers. "The HFCE power train has inherent energy efficiency advantages over the diesel ICE. Depending on the engine type and drive cycle, HFCE vehicles typically consume only 40% to 80% of the fuel consumed by an ICE vehicle to move a similar weight the same distance." The future price of hydrogen is more complex. Its cost depends on how it is produced, distributed, and prepared for consumption. Layzell, *et al.* [16] explore this question in detail with the general conclusion that as the scale of production increases hydrogen will be competitive with diesel fuel in Canada.

The $100 million purchase price for this cargo airship is based on the general costs of smaller modern airship designs, allowing for economies of size. The amortization period assumes 25 years in service. Insurance is set at 5% of aircraft replacement cost. Using these assumptions, the annual costs to operate this airship are presented in **Figure 7**. The total annual cost of the airship is the sum of annualized fixed costs ($14,000,000) and variable costs ($6,675,000) or $20,675,000. Based on the output of 89.1 t-km, the average round-trip costs per ton-km is $0.23/t-Km. The cost of moving 100 t of fresh tomatoes, 3000 km (by air) in a 100 t lift cargo airship would be US$69,000, or US69¢ per kg.

Recall that the cost of the traditional truck-based tomato supply chain is approximately US 59¢ per kilogram. In terms of direct costs, the 100 t lift airship is US 10¢ per kilogram more, at US 69¢ per kilogram. Being non-competitive in direct costs might not rule out the use of cargo airships. Consideration now turns to other competitive aspects concerning quality, shrinkage, and trade barriers.

Fixed costs	
Aircraft amortization (25 years @ 5%)	$7,000,000/yr
Insurance for airship	$ 5,000,000/yr
Administration and ground support	$ 1,000,000/yr
Maintenance and inspection	$ 1,000,000/yr
Total Annual Fixed Costs	$14,000,000/yr
Variable Costs	
Crews (9 persons @ $100,000)	$ 900,000/yr
Fuel ($1/L x 875 L/hr x 6600hrs)	$ 5,775,000/yr
Total Annual Variable Costs	$ 6,675,000/yr
Total Costs	$ 20,675,000/yr

Figure 7. 100-t Cargo Airship Cost per Year to Operate.

4.2. Quality and Shrinkage

The shelf life and shipping damage of fruits and vegetables depend on their hardiness. Tomatoes are a medium density vegetable, with a peak freshness of about 2 - 4 days. Imported fresh tomatoes are hand-picked when green and treated with a ripening gas (ethylene) at wholesale warehouses before moving to retail distribution. Shortening the time in transport by 65% or more, would provide greater flexibility for producers to harvest riper produce [17]. This should allow tomatoes transported by airships to command a price premium based on quality and freshness.

Shrinkage and quality deterioration can also occur because of bruising or poor ventilation. The shaking and jarring in transport, and transshipment at the border, discourage truck shipment of riper produce. Truck costs per t-km do not reflect quality losses of fresh produce in transit. An important feature of the Zeppelins is the lack of vibration. The smooth ride of airships would enable riper tomatoes to be transported and to minimize handling damage.

Vegetables packed in boxes have environmental requirements with respect to temperature, humidity and ventilation. Truck trailers have volume constraints that make it difficult to optimize air flow and temperature conditions. The cargo bay of an airship is limited only by weight. Fresh fruit and vegetable cargoes could be spread out to improve the shelf-life of the product.

Further research is required to establish values for the qualitative differences between trucks and airships. Logic suggests that the qualitative differences between the two modes of transport could exceed the monetary differences. For example, the reduced handling, faster transport, and minimal vibration could eliminate the shrinkage of perishable fruits and vegetables that occurs with overland shipping.

4.3. Non-Tariff Barriers and Trade Expansion

Airship transport from Mexico to Canada would eliminate the need to adhere to US phytosanitary rules, or bear the delays and costs of US Customs clearance. US Marketing Orders affect Mexican tomato exports from October 10 through June 15 of each year [18]. Specific tomato sizes are restricted based on the Florida tomato crop. The US has also forced a minimum import price on Mexican tomatoes exports that reduces their demand [19]. Airships would open up new markets for Mexican growers that are unrestricted. US phytosanitary regulations also affect several other products that are damaged by treatments (e.g., hot water dip for mangoes) in order to be allowed entry to travel in-bond across the US.

Avoiding the US border would expand the range of produce that could be exported to Canada from Mexico. For example, citrus exports from Mexico are prohibited from crossing the US overland because of the Mediterranean fruit fly. This insect is not a concern in Canada, but it effectively blocks the trade of citrus fruits from Mexico.

Each climate zone has its advantages. Canada can produce; grain-fed livestock, apples, potatoes and other foods, less expensively than tropical countries. Pork and processed products, root crops and tree fruit could provide return freight from Canada to Mexico in a temperature-controlled cargo airship. The round-trip would be competitive with trucking and expand the export of these Canadian food products.

It is worth noting that cargo airships could reach island countries like Cuba, and the Central American countries that are unable to use overland transport to Canada. This would create new opportunities for two-way trade of more agricultural goods. Beyond the narrow case of Canada and tomatoes, cargo airships could open many new trade routes and connections. Chile has substantial exports of fruits and vegetables, but for perishables like peaches and plums, sea transport generally takes too long. Anyone purchasing these products in Canada knows that they are often disappointingly browning on the inside. Chile would become a much stronger competitor to California, if they could reach North American markets in three days transport (9590 km from Santiago to Winnipeg).

4.4. Carbon Emissions of Refrigerated Trucks versus Cargo Airships

In terms of the carbon emissions saved, the amounts are impressive. A 100 t airship travels three times as fast as a reefer truck and carries five times more product. Consequently, it would take 15 reefer trucks to do the same amount of work as a 100-t lift airship. The 15 trucks would consume 21,525 L of diesel fuel each way. So, the round-trip total diesel consumption of these trucks would be 43,050 L. As mentioned earlier, a litre of diesel fuel contains 720 grams of carbon and when burned produces 2640 grams of CO_2. Each 100 t cargo airship would replace truck emissions of 114 t of CO_2 per trip, or 18,810 t per year (based on 165 annual trips).

Carbon pricing could have some impact on the competitiveness of airships and trucks, at least until long-haul trucking goes electric, too. The economic value of the carbon reduction is not included in the cost comparison, only noted, but its magnitude is worth consideration. As of July 1, 2023 the carbon tax in Canada will be C$65/t, or approximately US$49/t, and rising to C$170/t (US$128/t) by 2030. As calculated earlier, a one-way trip by a refrigerated truck produces 3.8 t of CO_2. At current carbon tax rates, this would add an additional US$186, or about US1¢ per kilogram to the transport costs. Although this more than doubles by 2030, it is insufficient to make up for the current cost difference ($0.59/kg for trucks versus $0.69/kg for airships).

5. Conclusions

Concerns about climate change and the desire to reduce GHG emissions have caused society to re-evaluate food consumption patterns. In general, the environmental impact of transportation is a relatively minor part of most food supply chain carbon-footprints. The exception is the transport of fresh fruits and vegetables. For at least, nine months of the year, they are carried long distances in refrigerated tractor-trailers. In total, the transport of perishable products from Mexico and the US to Canada creates an estimated 570,000 t of CO_2 emissions on an annual basis.

This study compares the economics of cargo airships powered by hydrogen fuel cells in place of diesel fuel-powered refrigerated trucks. An airship the size of a 1930 s' Zeppelin was used as a model for analysis. Specifically, the flight characteristics of a *Hindenburg* Zeppelin, with some allowances for 21st century technology, is assumed to carry 100 t of cargo. The analysis suggests that an airship of this size could be a competitive alternative to refrigerated tractor-trailers, considering the value of its service attributes.

In the future, refrigerated trucks could reduce emissions by being electrically-powered, and even further reduce costs by operating autonomously. This would make trucks more competitive, but cargo airships will also make technical improvements. Airships experience increasing economies of size. Given advances in materials and methods, rigid airships could be expected to easily double or triple the useful lift that they achieved 85 years ago. Moreover, research is underway to develop thin solar coverings that can take advantage of the airship's great size to produce green energy [20].

The cargo airship's greater transit speed and more delicate handling of produce may be the greatest challenge to refrigerated trucks. Airships will enable consumers to purchase fresher, more nutritious, better tasting fruits and vegetables during the nine months when local production does not exist. Cargo airships have broad appeal to those concerned about sustainable economic solutions. Buyers faced with the challenges of importing fresh produce will appreciate the logistical simplicity and quality differences that airships can offer.

Managerial and Policy Implications

This study is based on a snapshot in time and considers only one commodity, tomatoes. Given the need to make strong assumptions about the operations of a modern airship, extra precision in the analysis of market prices or the inclusion of other commodities would be unlikely to add much to the confidence of the findings. This must await the availability of modern airships to make direct comparisons. Such airships are coming. LTA Research has now inflated the *Pathfinder 1* that is the first rigid airship in 85 years [21]. This is a technology demonstrator, but they have plans to build rigid airships that lift 100 t and more.

This study employs the cruising speed of the *Hindenburg* that is 135 km/hr. It is unknown whether that speed was optimal for fuel consumption, as fast as its engines could push the airship, or the limits they wished to risk with the airframe. Structural failures are attributed to several accidents, including the *Shenandoah*, *Dixmude*, *Macon* and others [22]. Engineers in the 1930 s had only slide rules to work out the stress concentrations. With modern engineering, the cruising speed of a cargo airship could be faster. Higher velocities have a direct impact vehicle utilization, which reduces average cost.

Cargo airships could have a worldwide impact on north-south food distribution because they can offer point-to-point delivery. Avoiding a US land crossing would create export opportunities from tropical countries throughout Latin America and the Caribbean that are now excluded by water crossings, road distance or non-tariff barriers. Similarly, cargo airships would open new trade opportunities for African countries in the markets of Europe. The agricultural sectors of Europe and North America would also benefit because the airships could return south with loads of temperate zone products, like pork and potatoes, that are in short supply in the tropics.

The contribution of transportation to the "carbon footprint" of food supply chains has been dismissed as unimportant in the literature, compared to some much larger targets, like beef production. For most food supply chains, the contribution to GHGs of transportation are a small percentage of the total. However, this is not the case for fresh fruits and vegetables. The carbon emissions of refrigerated tractor-trailers that carry tropical fruits and fresh vegetables to Canada are substantial. As nations search for opportunities to slow climate change by reducing GHGs, cargo airships could become a competitive alternative to long-haul trucking, as well as cargo jets.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Long Branch Mike (2023) Phoenix Rises—Return of the Airship. London Reconnections. https://www.londonreconnections.com/2023/phoenix-rises-return-of-the-airship/

[2] Prentice, B.E. and Lau, Y.Y. (2016) Market Potential for Transport Airships in Service to Hong Kong. *International Journal of Aviation Management*, **3**, 68-83.

[3] Neal, C. and Koo, T. (2020) Demand for Cargo Airships: An Analysis of Mode Choice Decision Making in the Freight Transport Industry. *Journal of Air Transport Management*, **83**, Article ID: 101741. https://doi.org/10.1016/j.jairtraman.2019.101741

[4] Gordon, J.E. (1976) The New Science of Strong Materials: Or Why You Don't Fall through the Floor. Princeton Science Library, Princeton.

[5] Smith, A. and MacKinnon, J.B. (2007) The 100-Mile Diet: A Year of Local Eating. Random House of Canada Ltd, Toronto.

[6] Weber, C. and Matthews, H. (2008) Food-Miles and the Relative Climate Impacts of Food Choices in the USA. *Environmental Science and Technology*, **42**, 3508-3513. https://doi.org/10.1021/es702969f

[7] Wakeland, W., Cholette, S. and Venkat, K. (2012) Food Transportation Issues and Reducing Carbon Footprint. In: Boye, J. and Arcand, Y., Eds., *Green Technologies in Food Production and Processing*, Springer, Boston, 211-236. https://doi.org/10.1007/978-1-4614-1587-9_9

[8] Poore, J. and Nemecek, T. (2018) Reducing Food's Environmental Impacts through Producers and Consumers. *Science*, **360**, 987-992. https://doi.org/10.1126/science.aaq0216

[9] Ritchie, H. (2020) You Want to Reduce the Carbon Footprint of Your Food? Focus on What You Eat, Not Whether Your Food Is Local. Our World in Data. https://ourworldindata.org/food-choice-vs-eating-local

[10] AAFC (2022) Statistical Overview of the Canadian Fruit Industry 2021. Crops and Horticulture Division, Agriculture and Agri-Food Canada. https://agriculture.canada.ca/en/sector/horticulture/reports/statistical-overview-canadian-fruit-industry-2022

[11] AAFC (2022) Statistical Overview of the Canadian Field Vegetable and Mushroom Industry, 2020 Horticulture Section Crops and Horticulture Division Agriculture and Agri-Food Canada, December 2021. https://agriculture.canada.ca/en/sector/horticulture/reports/statistical-overview-canadian-field-vegetable-industry-2022#a2.3.4

[12] Prentice, B.E., Beilock, R.E., Phillips, A.J. and Thomson, J. (2005) The Rebirth of Airships. *Journal of the Transportation Research Forum*, **44**, 173-190.

[13] Gonzalez Alba, M. (2021) Plan De Exportación De Jitomate Mexicano ACanadá. Master's Thesis, Universidad Autonimo de Aquascalientes, Aguascalientes.

[14] Hindenburg Flight Operations and Procedures.

https://www.airships.net/hindenburg/flight-operations-procedures/

[15] Lof, J., MacKinnon, C., Martin, G. and Layzell, D.B. (2020) Survey of Heavy-Duty Hydrogen Fuel Cell Electric Vehicles and Their Fit for Service in Canada. *Transition Accelerator Reports*, **2**, 1-74.

[16] Layzell, D., Young, C., Lof, J., Leary, J. and Sit, S. (2020) Towards Net-Zero Energy Systems in Canada: A Key Role for Hydrogen. Transition Accelerator Reports. https://transitionaccelerator.ca/towards-net-zero-energy-systems-in-canada-a-key-role-for-hydrogen

[17] Estabrook, B. (2011) Tomatoland: How Modern Industrial Agriculture Destroyed Our Most Alluring Fruit. https://www.npr.org/2011/08/26/139972669/the-unsavory-story-of-industrially-grown-tomatoes

[18] USDA-AMS (2021) Importing Tomatoes. https://www.ams.usda.gov/rules-regulations/section8e/tomatoes

[19] Johnecheck, W.A., Wilde, P.E. and Caswell, J.A. (2010) Market and Welfare Impacts of COOL on the U.S.-Mexican Tomato Trade. *Journal of Agricultural and Resource Economics*, **35,** 503-521. http://www.jstor.org/stable/23243069

[20] Pflaum, C., Riffelmacher, T. and Jocher, A. (2022) Airship with Onboard Energy Harvesting—An Environmentally Friendly Mode of Transportation. https://www.researchgate.net/publication/364494640_Airship_With_Onboard_Energy_Harvesting_-_An_Environmentally_Friendly_Mode_of_Transportation

[21] Warwick, G. (2023) LTA's Large Rigid Airship Gets Airborne. Aviation Week. https://aviationweek.com/aerospace/advanced-air-mobility/ltas-large-rigid-airship-gets-airborne

[22] Toland, J. (1972) The Great Dirigibles—Their Triumphs and Disasters. Dover Publications Inc, New York.