Analysis of the Energy and Greenhouse Gas Emission Implications of Distributing and Refrigerating Beverages

Final Report

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1. Introduction

As a trade association for the aluminum production, fabrication, and recycling industry and its suppliers, the Aluminum Association has played a key role in efforts to understand the environmental impacts from aluminum products across their life cycles. One approach for understanding the life-cycle impacts of aluminum products is life-cycle assessment (LCA). As defined by the International Organization for Standardization (ISO) in its 14040 standard, LCA is a process that "addresses the environmental aspects and potential environmental impacts (e.g., use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e., cradle-to-grave)," (ISO 2006). A key stage in the LCA process is the life-cycle inventory (LCI) analysis, consisting of an inventory of input and output data for the system being studied.

Knowledge of the upstream (i.e., raw material production and manufacturing) and downstream (i.e., recycling or disposal) life-cycle environmental implications of beverage containers is fairly well-understood. In recent years, industry associations have worked to develop robust LCIs for a range of common packaging materials. For example, the Aluminum Association conducted an LCI of aluminum cans and ingot and examined the environmental impacts from the upstream and downstream stages of the life-cycle of aluminum materials (PE Americas 2010). Similarly, the American Chemistry Council issued a report compiling the cradle-to-gate LCI of several plastic resins, including those used to make most plastic beverage containers (FAL 2011). While these and other studies provide detailed analyses of the production stage and/or end-of-life impacts, much less attention has been dedicated to investigating use-phase impacts. This study seeks to examine greenhouse gas (GHG) emissions and energy consumption during the use phase of beverage packaging products, including how packaging influences transportation and refrigeration processes and related impacts.

With more and more companies considering the environmental impacts of their supply chains, increased scrutiny is placed on all phases of the life cycles of products and packaging. This includes distribution from manufacturers to retail locations and subsequent storage or refrigeration at retail locations. Beverage distribution impacts depend on product transportation efficiencies, which may be influenced by container type. For aluminum beverage cans and other packaging materials that are frequently refrigerated prior to beverage consumption, an assessment of the use phase must also consider the energy required for refrigeration and the high global warming potential (GWP) of gases used in refrigeration equipment.

Understanding the role of packaging and considering how national average use-phase practices in transporting and refrigerating packaged beverages influence these use-phase emissions could inform the relative importance of these phases on the full life-cycle impacts and could shed light on ways to increase efficiencies. While this study seeks to understand these impacts, it is limited by the wide variety of beverage package types in use, the range of distribution and refrigeration practices employed by different retail locations, and the availability of public information.

2. Goal and Scope

2.1. Goal of Study

The goal of this study is to provide the Aluminum Association and the aluminum industry greater insight on the life-cycle GHG impacts and energy use associated with the transportation and refrigeration of aluminum beverage containers and how these impacts compare to bottle alternatives. This study seeks to understand if there are energy-use and GHG emission benefits to using aluminum for beverage containers for certain retail and end-use locations in terms of: (a) transportation space efficiency during distribution, and (b) refrigeration efficiency, including both space and speed with which beverages can be cooled. This analysis applies life-cycle thinking and approaches, but is not an LCA in itself. Therefore, it does not present a final result for the life-cycle impacts of aluminum beverage containers; rather, the results are intended be taken in context with available studies on the upstream and downstream impacts of these packaging materials for a complete picture of life-cycle impacts. However preliminary results were presented at the American Center for Life Cycle Assessment LCA XV conference on October 8, 2015 in Vancouver, BC. Comments from the audience have been incorporated into this final report as appropriate.

Whereas LCAs of beverage packaging typically focus on the manufacturing and material recovery impacts of packaging, this study seeks to characterize the energy use and GHG emissions associated with distribution and retail. In previous studies, characterizations of beverage transportation and refrigeration have been simplified and may not take into account a number of material and shape-specific qualities of aluminum beverage containers. The primary qualities this study seeks to assess include:

- **Space Efficiency:** Container dimensions impact the packing efficiency in beverage distribution vehicles and the storage efficiency in refrigerators. Compared to bottles, aluminum cans have a higher volume-to-surface area ratio and can therefore be used to transport or refrigerate a greater amount of beverage product per unit of transportation or refrigeration volume. Additionally, differences in secondary packaging (i.e., additional packaging for distribution) requirements between cans and bottles may further influence differences in efficiency across container types.
- **Material Properties (thickness and conductivity):** The difference in material thickness between aluminum and alternatives plays a role in determining container weight, which has already been commonly factored into LCAs; however, relative container thickness may also affect containers' heating and cooling rates. Certain beverage packaging materials and greater surface area of containers allow for faster cooling of beverages.

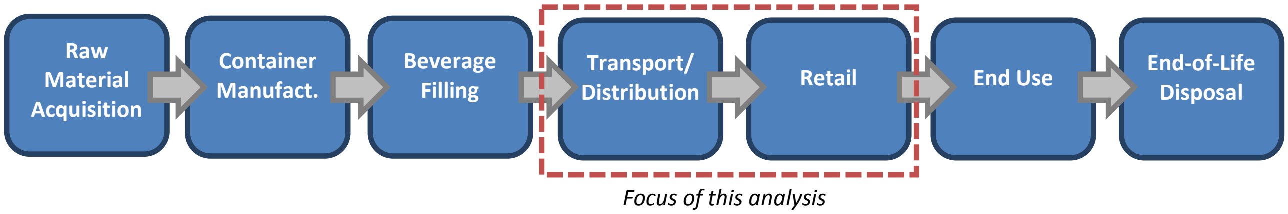
2.2. Scope

The scope of this study comprises an analysis of the transportation and refrigeration of beverage containers, using an LCA approach to characterize the GHG and energy use impacts of these life-cycle phases.

2.2.1. System Boundaries

Figure 1 provides a graphical overview of the system boundaries of this study. As the study includes only the environmental impacts associated with the use phase of a beverage's container. Upstream and downstream contributors to a beverage's overall life cycle, such as the manufacture of a beverage itself or recycling or disposal, are considered outside the scope of this analysis. For a more detailed overview of the included and excluded components of the beverage life-cycle, see Table 1.

Figure 1: Scope of Analysis within the Life Cycle of Beverage Container



The product examined in this study is a standard 12-fluid-ounce aluminum beverage can, with consideration of its GHG and energy impacts to comparable glass bottles and Polyethylene terephthalate (PET) bottles. This study does not account for individual preferences for one type of container versus another. Because of variance between beverage volumes and between container types, results are normalized across container types in volumetric units of liquid product.

Table 1: Included and Excluded Components of the Beverage Container Life Cycle in this Report

Included	Excluded
• Distribution from filling facility to retailers • Refrigeration at retail • Refrigeration at home	• Raw material extraction and processing • Cradle-to-grave impacts of secondary packaging for distribution • Container manufacturing • Beverage manufacturing and filling • Distribution to consumer • End-of-life disposal

The study focuses on what can be reasonably quantified and compared: (a) distribution of packaged beverages from centralized manufacturing and filling facilities to retail or end-use locations and (b) refrigeration at specific retail or end-use locations with a focus on supermarkets, small market/convenience stores, and restaurants. The study focuses on these retail uses because they represent dominant practices for beverage sales in the United States. While beverage refrigeration practices at bars may closely resemble those at restaurants, bars are not explicitly included in the scope of this analysis based on data availability. Transport and refrigeration at other retail locations—such as liquor stores, beverage wholesalers, entertainment venues, and institutional dining facilities—are also not included in the scope of this analysis. Refrigeration at homes, while not part of the initial scope, was included for an illustrative comparison because data were available. However, there is a high degree of uncertainty associated with consumer practices in transporting beverages from retail locations to their home. Due to a lack of available data on national average beverage transportation distances and modes from retail to home, this study does not evaluate transportation of beverages to homes.

2.2.2. Functional Unit

The functional unit of this analysis is 1 liter of beverage (carbonated soft drink or beer) delivered to the consumer at a retail location—a supermarket, small market/convenience store, or restaurant. Results are also provided in terms of a representative scenario wherein beer and soft drinks are shipped to retail in order to compare the environmental impacts on a product level.

2.2.3. Environmental Impacts

This study focuses on energy use and GHG emissions associated with fossil fuel combustion during transportation and electricity used to power refrigerators. Refrigeration GHG emissions also include fugitive emissions of refrigerants. Emissions from upstream production of fuels used in electricity are not included.

2.2.4. Geographic and Temporal Coverage

This study characterizes beverages distributed and stored in the United States, using the most recent data available. The temporal coverage of this study is intended to reflect the present day, as this study includes feedback from stakeholders on current practices for beverage storage and distribution. To address certain data gaps, older information (e.g., prior to 2005) and data from outside of the United States were used, as indicated in the text.

2.2.5. Impact Assessment Method

The metrics used for assessing the environmental impact of beverage containers are GHG emissions and cumulative energy demand, in grams of carbon dioxide equivalents (g CO_2e) and megajoules (MJ) of energy, respectively. GHG emissions are expressed as CO_2-equivalents using the 100-year Global Warming Potentials (GWPs) provided by the Intergovernmental Panel on Climate Change (IPCC) in its 2007 Fourth Assessment Report (IPCC 2007). Energy use is expressed in terms of primary energy.

3. Approach

This section summarizes the approach used to conduct the analysis of energy and GHG impacts from the use phase of beverages described in this report. The approach included the following key steps: (a) defining the information and data needs for the analysis of the distribution and refrigeration phases; (b) a literature search to develop initial estimates of energy use and GHG emissions; (c) outreach to stakeholders in the beverage, distribution, and retail industries to fill data gaps; and (d) refinement of energy use and GHG emissions.

3.1. Define Information and Data Needs

The first step in the analysis was to define the information and data needs in order to accomplish the goal of this study within the project scope outlined in Section 2. For modeling beverage distribution from filling locations to retailers, ICF sought to identify data for estimating the energy and GHG impacts from national average transportation practices for common aluminum, glass, and plastic beverage containers. Using national average practices for the three container materials does not capture the precise energy and GHG impacts for a specific beverage distribution chain, but it provides a basis for comparing impacts across beverage container materials.

To model beverage distribution, we sought data on the shipping practices and distances typically used to distribute the beverages addressed in this study. This includes:

- Average shipping distances from can/bottle filling plants to retail locations;
- Typical vehicle types and sizes;
- Typical vehicle volume and weight capacities;
- Fuel types used and fuel consumption in relevant vehicles;
- Share of beverages refrigerated during distribution, by beverage and container type;
- Secondary packaging used during beverage transport; and
- Volume and weight per unit of beverage during transport.

Similarly, for beverage refrigeration at retail locations, we sought to identify data necessary for estimating the energy and GHG impacts from national average refrigeration practices for aluminum, glass, and plastic beverage containers in cooling equipment typically used in restaurants, bars, supermarkets, and liquor stores.

To model beverage cooling, we sought data on the material properties of container materials and cooling and retail practices used for the beverages addressed in this study. This includes:

- Heat transfer efficiency of beverage container materials;
- “Chill to” temperatures typically used at retail locations;
- Average turnover rates across the relevant retail locations;
- Share of different beverages chilled;
- Refrigeration types and related cooling efficiency;
- Typical cooler sizes;
- Annual refrigerant leak rate; and
- Types of refrigerant typically used in retail coolers.

In an attempt to assess the total impacts from cooling of beverages in the United States, ICF sought data on the relative shares of beverages sold at different retail locations (e.g., the percent of soda cans and bottles sold at small convenience stores versus supermarkets).

3.2. Perform Literature Search to Develop an Initial Estimate of Energy Use and GHG Emissions and Identify Data Gaps

After defining the data needs for this project, we performed a literature search to locate data and other information that would help inform an initial estimate of energy and GHG emissions from transportation or distribution and refrigeration of beverage containers.

The literature search involved examining data and information available from a variety of sources, including reports issued by U.S. government agencies, peer-reviewed journals, life-cycle inventory (LCI) databases, industry groups, and other sources. ICF reviewed LCI data in the Ecoinvent database and the U.S. LCI Database for information that could help us quantify the impacts during beverage use (Ecoinvent Centre 2007, NREL 2012). The Ecoinvent database was also used to extract emissions estimates for processes such as freight transit. In addition, ICF sought data from studies characterizing the dimensions and material properties of a variety of beverage packages and materials in order to conduct its own material properties analysis and compare cooling rates.

ICF also searched for relevant information through a number of beverage, distribution, and retail industry groups, including the Beverage Industry Environmental Roundtable (BIER), American Beverage Association, Beer Institute, Brewers Association, National Beer Wholesalers Association, National Association of Convenience Stores, National Association for the Specialty Food Trade, Beverage Trade Network, and the National Grocer’s Association. Through this process, ICF developed an initial set of assumptions for modeling beverage use phase emissions in Excel.

To fill data gaps and to complement the information collected from studies as part of the literature review, ICF identified and reached out to various stakeholders in the beverage, distribution, and retail industries.[1]

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[1] The organizations that responded and provided input through either a phone interview or by email included: Powers Distributing, Hussmann Corporation, Pacific Northwest National Laboratory, and Ball Corporation.

Using information gathered from the initial research, ICF developed preliminary estimates of the energy and GHG emissions associated with the beverage distribution and refrigeration whenever possible, and summarized the key findings from the literature review in a memorandum. The preliminary estimate highlighted key data elements needed for the assessment, served as a document of our assumptions early-on in the analysis, and helped identify critical data gaps where additional information is needed.

3.3. Finalize Energy Use and GHG Emissions Estimates

Based on the information collected, ICF developed a parameter-based spreadsheet model of the relevant life-cycle stages (i.e., distribution and retail) for each beverage type (i.e., plastic, glass, and aluminum). The spreadsheet generated results in terms of both energy demand and GHG emissions, and was able to provide comparative results between different beverage container types.

The final analysis incorporated distinct unit process level data for the two main beverage use-phase processes: distribution and refrigerated storage. It also included findings on the material properties of glass, plastic, and aluminum cooling efficiencies, which fed into the refrigerated storage analysis. These data were combined to estimate the GHG emissions and energy demand from these two phases while excluding the life-cycle phases described in the scope section above, such as the beverage and containers themselves. Additionally, the model includes a representative scenario in which beer and soft drinks are shipped an average distance in a large truck to a small market/convenience store.

GHG emission results are presented in terms of CO_2 equivalents using GWP factors and energy use results are presented in terms of megajoules. ICF did not attempt to develop life cycle inventory assessment (LCIA) impact category information of any other impacts beyond climate change.

4. Overview of Packaged Beverage Practices

This section provides a very brief overview of packaged carbonated soft drink and beer practices in the United States, with a focus on (a) container types considered in this analysis, (b) practices during distribution to retail, and (c) refrigeration practices at supermarkets, small market/convenience stores, and restaurants.

4.1. Container Types

Nearly 78 percent of carbonated soft drinks sold in the United States were packaged (versus fountain) in 2003 (Beverage Marketing Corporation 2013). Soft drinks are packaged in 12-oz aluminum cans and various sizes of plastic and glass bottles. Beer is packaged typically in glass bottles or aluminum cans.

For the purposes of comparison and based on data availability for this analysis, beverage containers were narrowed to four types: a 12-oz aluminum can, a 12-oz glass bottle, a 16.9-oz PET plastic bottle, and a 20-oz PET plastic bottle. Illustrations for the first three container types are shown in Appendix A. These bottles and cans are packaged in boxes or cartons and further in pallets. The materials required in packaging are trays, tray liners, boxes, cartons, corrugated cardboards, LDPE stretch wrap and wooden pallets (Denmark EPA 1998; Climate Conservancy 2008). These materials are referred to later in this study as “secondary packaging”, in contrast to bottles and cans themselves, which are defined as “primary packaging”. Aluminum cans are held in corrugated cardboard trays, cardboard boxes, or secured with LDPE carriers (Denmark EPA 1998); glass bottles are held in cardboard cartons secured with LDPE wrap (Climate Conservancy 2008); and plastic bottles are held in cardboard trays secured with LDPE wrap (Dettore 2009). Further details of the packaging for each container type are provided in Section 5.1.

4.2. Distribution Practices

In this analysis, distribution refers to the hauling of beverages from filling locations to retail point of sale, typically on trucks. Filled cans and bottles are secured in secondary packaging for transport on wooden pallets. The pallets measure 40 by 48-inches and are re-used (Singh et al. 2011). A single wooden pallet has the following capacities for each beverage container type included in this analysis: 2,376 aluminum cans (Denmark EPA 1998); 1,296 glass bottles (Climate Conservancy 2008); and 1,728 plastic bottles (Dettore 2009).

The pallets are loaded into different bays of trucks. A "bay" refers to a storage space on a beverage truck with space for one pallet worth of products and accessible with an individual sliding door. A wide variety of trucks are used to distribute beverages, including medium-size trucks for local distribution and tractor-trailer trucks for long-distance hauling. Figure 2 shows an example of a beverage truck with bays.

Figure 2: An Example of a Beverage Truck Pallet

Source: U.S. Occupational Safety & Health Administration, Beverage Delivery Ergonomics[2]

Beer and soft drinks are not typically refrigerated during shipping because they are sealed, chemically stable, and unlikely to spoil (BIER 2012a, BIER 2012b). In cases where refrigerated trailers are used, the overall fuel consumption for the vehicle is estimated to increase by approximately 20 percent (Lalonde et al. 2013). However, due to lack of data on the share of beverages refrigerated during distribution, additional energy and GHG emissions from refrigerated distribution are not assessed in this study.

4.3. Retail Practices

At retail or end-use locations, packaged soft drinks and beer are stored either at room temperature or refrigerated, with this analysis focusing on the refrigeration impacts. One study estimates that average refrigeration time at retail for a six-pack of beer is one week (The Climate Conservancy 2008).

Supermarkets often have both open and glass-door cases attached to their full store-wide system as well as smaller display cases up front near the registers. Convenience stores will usually have stand-alone display cases with glass doors and/or larger cases that can be stocked from the back. Restaurants with bars will usually get their beverages from the bar area, and/or may store beverages in their walk-in coolers in the kitchen. Supermarkets typically have about 60 refrigerated display cases of which glass door cases are more efficient than open door cases (DOE 2009).

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[2] https://www.osha.gov/SLTC/etools/beverage/delivery_trucks.html

For the retail or end-use locations included in this analysis, four refrigerator types were considered:

- A twelve-foot supermarket display (Hussmann D5X-E);
- A small market/convenience store refrigerator (Hussmann BCH-18);
- A single-unit restaurant refrigerator (Delfield 6025XL-S); and
- A typical home refrigerator.

These refrigerators are shown in Figure 3. The supermarket and small market refrigerators models were also referenced in the Climate Conservancy's report, with technical specifications drawn from their manufacturer. As Hussmann does not manufacture refrigerators for the restaurant use, inventory from a competitor manufacturer was chosen as a representative unit. The home refrigerator was based on a refrigerator modeled by the Climate Conservancy (2008). While home refrigeration was not part of the initial scope, data were available that allowed for inclusion of the cooling phase.[3]

Figure 3: Refrigerator Models Chosen

Home Refrigerator

Small Market/Convenience Store Refrigerator

(Hussmann BCH-18)

Restaurant Refrigerator (Delfield 6025XL-S)

Supermarket Refrigerator (Hussmann D5X-E)

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[3] Transportation from the retail location to the purchaser's home was not evaluated.

5. Energy Use and GHG Emission Impacts

This section presents the GHG emission and energy use impacts associated with transportation space efficiency and refrigeration efficiency for aluminum cans relative to glass and plastic beverage containers. This section includes a summary of key data sources, assumptions, calculations, and results for the transport and cooling stages of the beverage use phase with a focus on space efficiency. The results for a separate analysis looking at material cooling efficiency are then presented. Finally, this section provides an assessment of the potential GHG impacts for a representative distribution and cooling scenario and for national U.S. beverage sales.

5.1. Transportation Efficiency

This subsection provides the results of the analysis of transportation space efficiency energy use and GHG impacts of using aluminum cans relative to glass and plastic bottles. It describes the key data sources and assumptions that drive the analysis of benefits associated with transportation/distribution to the different retail types, shows the calculations used, and presents the energy use and GHG emission results.

5.1.1. Key Data Sources and Assumptions

This analysis incorporated information and data from a variety of life-cycle studies, including:

- the Beverage Industry Environmental Roundtable's (BIER) *Research on the Carbon Footprint of Beer* (2012a),
- *Research on the Carbon Footprint of Carbonated Soft Drinks* (2012b),
- Climate Conservancy (2008), *The Carbon Footprint of Fat Tire Amber Ale,*
- Denmark Environmental Protection Agency (EPA) (1998), *Life Cycle Assessment of Packaging Systems for Beer and Soft Drinks*,
- Lalonde et al. (2013) *Life Cycle Assessment of Beer in Support of an Environmental Product Declaration. Institute for Environmental Research and Education,* and
- Singh et al. (2011) *Life Cycle Inventory of HDPE Bottle-Based Liquid Milk Packaging Systems*.

This was supplemented with truck distribution data from the U.S. Department of Transportation's Commodity Flow Survey (DOT 2014a, DOT 2014b) and outreach to stakeholders, including beverage distributors and packaging manufacturers. Further information used to support this study includes LCI data on truck transport, glass, plastic, and aluminum from the U.S. LCI and Ecoinvent databases (NREL 2012, Ecoinvent Centre 2007).

This analysis focused on domestic transport of packaged soft drink and beer beverages by delivery truck.[4] The analysis considers two main distribution stages: (a) transport of beverages from manufacturer or bottler to regional warehouse or distributor, and (b) transport of beverages from regional warehouse or distributor to retail. The Commodity Flow Survey reports ton-miles and mileage information covering those stages for beer transported in small trucks and medium/large trucks, as well as in private and for-hire trucks regardless of size (DOT 2014a). Thus, for beer, ICF estimated emissions for the different truck types and this analysis reports weighted average emissions for small and large truck distribution. Emission estimates for private and for-hire trucks transporting beer present low and

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[4] A much smaller quantity of packaged beverages is transported via rail, water, and air shipments. The emissions from those shipments are not examined in this study.

high ranges, respectively, and are provided to show the sensitivity of results to different transportation distances. For the lower and upper bounds, ICF assumed a large truck was used for the factory-to-wholesale stage and a small truck for wholesale-to-retail stage.

For soft drinks, the Commodity Flow Survey provides an aggregated mileage value that is not broken out by distribution stage or truck type (DOT 2014b). ICF assumed distribution of soft drinks by large truck due to data limitations as well as the assumption that the largest segment of beverage distribution would entail long-distance transport by large truck.

The analysis sorts distribution by beverage delivery trucks by their emissions and storage capacity. Truck storage capacity is measured in terms of both mass and number of bays. Based on the unit processes available for road freight transit in the Ecoinvent database, truck sizes were organized based on three categories of tonnage provided in the database: small trucks are assumed to range from 3.5 to 7.5 tons; medium trucks range from 7.5 to 16 tons; and large trucks correspond with the BIER studies' assumptions of a Class 8 tractor trailer weighing over 16 tons (BIER 2012a; BIER 2012b; Ecoinvent Centre 2007). ICF's corresponding assumptions for freight capacity were that a small truck holds 6 pallets, a medium truck holds 12 pallets, and a large tractor-trailer truck carries 20 pallets. These assumptions were based on an analysis of the various sizes and capacities of beverage delivery trucks from an industry source (Betten Trucks 2014).

ICF modeled a "typical" small truck using distances for trucks with 1,000 to 9,999 lbs shipment size as defined in the Commodity Flow Survey and emission factors for trucks with 3.5 to 7.5 tons GVW from Econinvent. Based on the assumptions used in the Beverage Industry Environmental Roundtable (BIER) reports, ICF assumed that a "typical" large truck would be a Class 8 tractor trailer with an empty mass of 33,000 lbs. and a maximum filled gross vehicle weight rating (GVWR) of 80,000 lbs[5] (BIER 2012a; BIER 2012b; Ecoinvent Centre 2007). This is the approximate North American equivalent of the 16-metric ton lorry cited in the two BIER studies. ICF modeled emissions from transportation in large trucks using distances for trucks with 10,000 to 99,999 lbs. shipment size as defined in the Commodity Flow Survey and emission factors for trucks with over 16 metric tons GVW[5] from Ecoinvent. ICF did not include backhaul of empty trucks from retailers to factories. However, because the emissions from returning empty trucks would not include the impacts of different packaging options this would not impact the comparative analysis. Finally, ICF assumed that all beverage trucks use diesel fuel (BIER 2012a, BIER 2012b).

5.1.2. Calculations

In order to estimate the emissions associated with beverage transport, ICF first estimated the ratio of packaging to liquid product for each of the three container alternatives. ICF calculated the mass of a loaded pallet by summing the mass of the primary packaging (e.g., the bottle or can) and the secondary packaging (e.g., cardboard trays and LDPE wraps, and the pallet itself). From there, the mass of the liquid product was divided by the total mass of the loaded pallet to determine the ratio of liquid product to packaging, as shown in Figure 4. Table 2 provides an overview of how the total mass per pallet for each of the three beverage container alternatives was constructed and the ratio of liquid product to total mass. The ratio is highest for 16.9-ounce plastic bottles at 0.94, followed closely by aluminum cans and 20-ounce plastic bottles at 0.93. The ratio is lowest for glass bottles at 0.60 given that a greater mass of secondary packaging is needed during transport to protect against breakage.

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[5] "Gross vehicle weight rating" refers to the maximum allowed operating mass of the vehicle in operation, including passengers and cargo.

Table 2: Mass of Packaging and Product for Aluminum, Glass, and Plastic Containers on a Per-Pallet Basis

Container/Material Type	Quantity	Total Mass (kg)
Aluminum Cans		
per pallet		
338 ml can	2,376	31.70
Tray (24 cans)*	99	5.94
Tray Liner*	99	0.65
Box (24 cans)*	99	3.37
Box (6 cans)*	396	4.95
LDPE Carrier (6 cans)*	396	0.34
Wooden Pallet	1	15.88
Packaging Weight per Pallet (including Pallet)		**62.8**
Mass of Beverage		843.5
Liters/metric ton cargo		0.93
Total Weight per Pallet (including Pallet)		**906.3**
Glass Bottles		
per pallet		
12-oz (355ml) beer bottle	1,296	261.36
Carton (24 bottles)	54	10.80
6-pack box	216	20.57
LDPE stretch wrap	1	0.08
Wooden Pallet	1	15.88
Packaging Weight per Pallet (including Pallet)		**308.7**
Mass of Beverage		460.1
Liters/metric ton cargo		0.60
Total Weight per Pallet (including Pallet)		**768.8**
16.9-oz Plastic Bottles		
per pallet		
16.9-oz plastic bottle	1,728	26.09
Plastic bottle caps	1,728	3.63
Corrugated cardboard tray (24 bottles)	72	5.98
LDPE Stretch Wrap	72	2.12
Wooden Pallet	1	15.88
Packaging Weight per Pallet (including Pallet)		**53.7**
Mass of Beverage		864.0
Liters/metric ton cargo		0.94
Total Weight per Pallet (including Pallet)		**917.7**
20-oz Plastic Bottles		
per pallet		
20-oz plastic bottle	1,296	30.24**
Plastic bottle caps	1,296	2.72
Corrugated cardboard tray (24 bottles)	54	5.38
LDPE Stretch Wrap	54	1.91

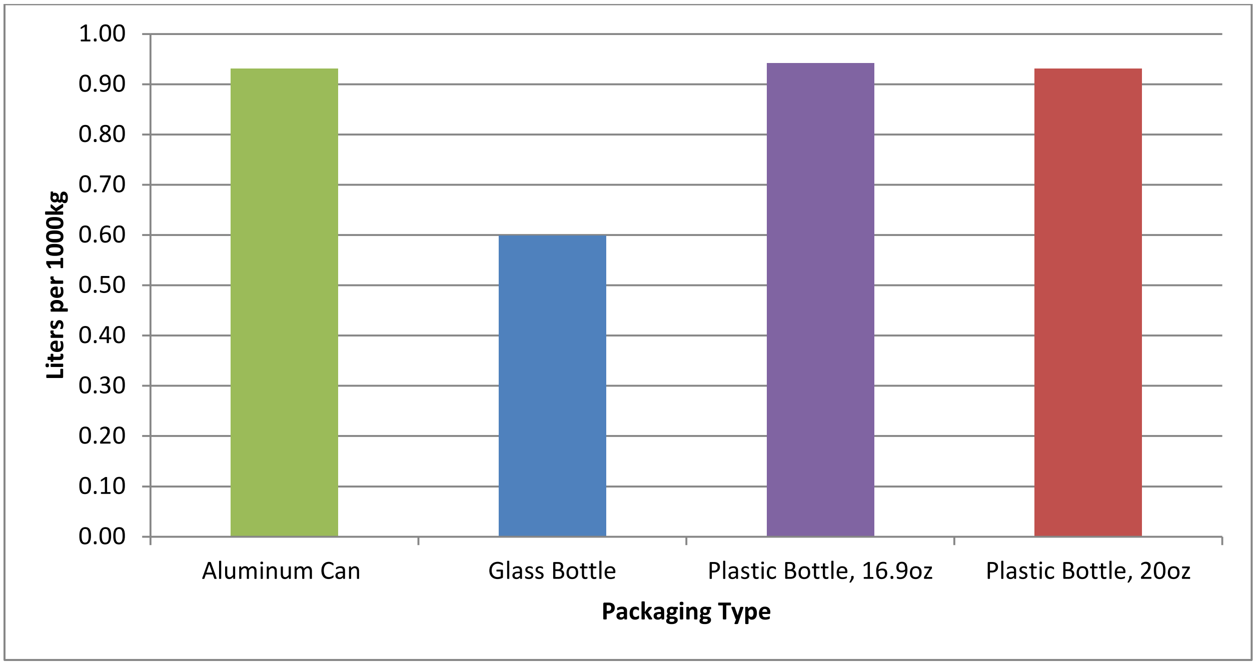
Container/Material Type	Quantity	Total Mass (kg)
Wooden Pallet	1	15.88
Packaging Weight per Pallet (including Pallet)		**56.1**
Mass of Beverage		766.5
Liters/metric ton cargo		0.93
Total Weight per Pallet (including Pallet)		**822.7**

Sources: Denmark EPA 1998, Climate Conservancy 2008, Dettore 2009, PE Americas 2010, Amcor Plastics 2010, Clear Mountain Water 2015.

* Secondary packaging for aluminum cans is weighted by its respective market share (i.e., trays vs. boxes), per Denmark Environmental Protection Agency (1998).

** Calculated using the average weight of five 20-oz bottles used for carbonated beverages from Amcor Plastics (2010).

Figure 4: Ratio of Liquid Product to Total Pallet Mass, by Container Type



To estimate emissions from the three pallet configurations, ICF assumed that small, medium, and large trucks would haul 6, 12, and 20 pallets, respectively. The mass of a fully-loaded pallet was then multiplied by emission factors for three separate types of freight transit derived from the Ecoinvent database and the U.S. LCI Database (Ecoinvent Centre 2007; NREL 2012). The final emissions are presented in a functional unit of grams of CO_2 equivalents per liter (g CO_2e/L).

5.1.3. Energy Use and GHG Emission Results

The initial literature review and discussions with stakeholders indicated that transportation efficiency is *both* volume and mass-constrained. These aspects, as well as a third interrelated driver of pallet efficiency are described below.

- Volume efficiency (sometimes called "cube efficiency" in distribution) was found to be the largest factor in differentiating the energy use associated with transporting beverages in different packaging formats. When a distribution truck is filled to capacity with beverages, the limiting factor is storage volume, not weight.

- Mass efficiency is secondary in impact to cube efficiency. Aluminum cans are much lighter than glass containers and slightly lighter than PET. Different types of secondary packaging, such as plastic shrink wrap to secure cases of beverages on a pallet, or cardboard boxes to hold sets of cans, are also used and contribute to the total weight hauled.
- Pallet efficiency is how well beverages are stored on each pallet and in each truck. It is a factor that is imposed by the design of beverage trucks taking into account the number of storage bays available per truck, with only one pallet fitting into each bay. For each pallet, the mass ratio of liquid beverage to total packaging dictated the relative efficiency of each container type across scenarios. The cylindrical shape and lower ratio of surface area to volume for aluminum cans allows for more units to be stacked per pallet and thus more units per truck load despite hauling the same number of pallets.

The final emissions associated with the transport phase are presented in Table 3 below. Results are shown as the GHG emissions from transporting one liter of beverage in each type of container.

Due to the similar volume efficiency and container mass of plastic bottles and aluminum cans, the difference in emissions for those container types carrying soft drinks is less than 1.5 percent; emissions from transporting beverages in glass bottles, in contrast, were 56 percent higher than those of aluminum cans.

A given truck carrying aluminum cans or plastic bottles generates higher emissions on a per truck basis than one carrying glass bottles because the total shipment has more mass. However, since a truck can carry approximately 50 percent more liquid in aluminum or plastic packaging than with glass, the final emissions per unit of beverage product are significantly lower. Additionally, the results indicate significant efficiency gains as the size of the truck increases, with smaller trucks emitting roughly 60 percent more GHGs per unit of product than large tractor-trailers.

Table 3: Transportation Phase Emissions and Energy Demand for Beverage Transport

Beverage, Truck Type	Aluminum Cans	Glass Bottles	16.9-oz Plastic Bottles	20-oz Plastic Bottles
GHG Emissions (g CO_2e/L)				
Beer Average	71	111	NA	NA
Lower Bound (Private Trucks)	27	42	NA	NA
Upper Bound (For-Hire Trucks)	154	239	NA	NA
Soft Drink Average	40	62	40	40
Energy Demand (MJ/L)				
Beer Average	0.97	1.51	NA	NA
Lower Bound (Private Trucks)	0.38	0.59	NA	NA
Upper Bound (For-Hire Trucks)	2.12	3.29	NA	NA
Soft Drink Average	0.54	0.85	0.54	0.54

5.2. Refrigeration Storage Efficiency

This subsection evaluates the refrigeration energy use and GHG impacts of aluminum cans relative to glass and plastic bottles in different retail markets or end-uses, focusing on the efficiencies related to refrigeration space. We describe the key assumptions that drive the analysis of energy use and GHG emissions associated with refrigeration in the different retail or end-use types, show the calculations used, and present the energy use and GHG emission results.

The two sources of GHG emissions included in the analysis of refrigeration storage efficiency are emissions from the electricity consumed to power the refrigerators and the fugitive emissions of refrigerants. Commercial refrigerants such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) contribute to the deterioration of the stratospheric ozone layer. Additionally, CFCs, HCFCs, and even the ozone-friendly hydrofluorocarbons (HFCs), contribute to global warming. HFCs, HCFCs, and CFCs typically have GWP ranges from 1,200 to 10,900 whereas carbon dioxide (CO_2) has, by definition, a GWP of one, as shown in Table 6. In fact, fluorocarbon refrigerants are up to 11,000 times more potent compared to CO_2 on a per molecule basis (EPA 2011).

Table 4: Global Warming Potential (GWP) Values for Common Commercial Refrigerants over a 100-Year Time Horizon

Refrigerant	GWP
CFC-12	10,900
R-502	4,657
R-507A	3,985
R-404A	3,922
R-407A	2,107
HCFC-22/R-22	1,810
R-407C	1,774
HFC-134a	1,430
Propane (R-290)	3.3
CO2 (R-744)	1
Ammonia (R-717)	0

Source: EPA 2014d.

These chemicals have a tendency to leak throughout the various phases of their transport and use. In a given supermarket's refrigeration system, leaks can occur in a variety of locations across the array of the system's components including display cases, compressor racks, condensers, and the piping and joints. Based on this information, we modeled refrigerant leakages using an example of each refrigerator type typical of the chosen retail markets, its specific refrigerant, and refrigerant charge. The annual leakage rates and refrigerant charge are based on the refrigeration retail or end-use type.

5.2.1. Key Data Sources and Assumptions

This analysis describes the retail or end-use locations, in particular refrigeration practices at restaurants, supermarkets, and convenience stores, that were chosen to assess use-phase impacts from beverages in the United States. ICF assumes that all beverages, regardless of retail location or end-use, are refrigerated for one week. This assumption was based on internal data developed by the New Belgium Brewery on the average refrigeration time at retail for a six-pack of beer presented in "The Carbon Footprint of Fat Tire Amber Ale" by The Climate Conservancy (2008). Each refrigerator was assumed to be filled to capacity, as no information was available on average refrigeration capacity.

The analysis in this section assumes a scenario where beverages are cooled for a given period of time, regardless of container, and refrigeration space is optimized (i.e., refrigerators are fully loaded to capacity).The energy consumption and GHG emissions per beverage container, during the refrigeration portion of the beverage use phase, are dictated by the volume of the containers, the beverage capacity of refrigerators typically used at each retail or end-use type, the energy consumption of the specific refrigerators, and the rate of fugitive refrigerant leakage. For each retail or end-use type, we chose a refrigerator model representative of typical cooling practices. Four refrigeration retail or end-use types were chosen: a large supermarket display, a small market or convenience store single unit, a single door restaurant refrigerator, and a home refrigerator (as shown in Section 4.3). Although we modeled a home refrigerator, the transportation impacts from retail location to homes are not included in this report.

Refrigerator capacity, home refrigerator electricity consumption, and beverage cooling time were taken from The Climate Conservancy's *The Carbon Footprint of Fat Tire Amber Ale* (2008) and supplemented by technical information from manufacturers. The supermarket refrigerator was based on Hussmann's D5X-E - 12 foot model, and the small market/convenience store refrigerator was based on Hussmann's BCH-18 model (Hussmann Corporation 2012, Hussmann Corporation 2014a). As Hussmann does not manufacture refrigerators for restaurant use, the restaurant refrigerator was based on Delfield's 6025XL-S model (Delfield 2013).

The functional cubic volume each beverage container type was determined based on a literature review of the container's length, width, and height. The 12-oz aluminum can specifications were based on those taken from Ball Corporation (Ball Corporation 2014). The 16.9-oz plastic bottle specifications were based on the technical specifications provided by Esterform Packaging (Esterform Packaging 2013). In addition, specifications for a 20-ounce plastic bottle were also located and included in this analysis based on Royal Vendor's Coca Cola Contour 20-ounce bottle (Royal Vendors 2014). The 12-ounce glass bottle specifications were based on the technical specifications provided by Owens Illinois (Owens Illinois Inc. 2012). Specifications for a 12-ounce glass bottle six-pack were provided by the Climate Conservancy (Climate Conservancy 2008). These specifications can be found in Table 7.

Table 5: Beverage Container Specifications

Standard Packaging Dimensions	Length (in)	Width (in)	Height (in)	Functional Cubic Volume (ft^3)	Beverage Volume per Container (L)
Glass bottle (12 oz)	2.40	2.40	9.09	0.03	0.355
Glass bottle 6-pack	7.20	4.80	9.09	0.18	2.130
Aluminum can (12 oz)	2.69	2.69	4.81	0.02	0.355
Plastic bottle (20 oz)	2.87	2.87	8.91	0.04	0.591
Plastic bottle (16.9 oz)	2.57	2.57	8.48	0.03	0.500

This analysis assumed that refrigerators for each retail or end-use type were efficiently filled to capacity with a single beverage container type (aluminum cans, glass bottles, or plastic bottles). As noted in Section 4.3, we also assumed that beverage containers are typically refrigerated for one week between distribution and purchase (Climate Conservancy 2008). The capacity of each refrigerator was based on its recommended "usable cube", or the space within the refrigerator that can accommodate objects for cooling.

The home refrigerator capacity was based on assumptions provided in the Climate Conservancy's evaluation of New Belgium Brewery's beer (Climate Conservancy 2008). The report assumed that a glass bottle six pack of beer's volume is 1/40th of the cubic volume of a home refrigerator (The Climate Conservancy 2008). The functional cubic volume of a glass bottle six pack was multiplied by forty in order to determine the home refrigerator's cubic volume. The electricity demand for the home refrigerator was assumed to be the average of the maximum energy consumption for new home refrigerators sold in the U.S. in 1993 (490 kWh) and 2001 (410 kWh), or 450 kWh per year (The Climate Conservancy 2008). These specifications are presented in Table 9 below.

Table 6: Refrigerator Models, Energy Demand, and Usable Cube by Retail or End-Use Type

Retail or End-Use Type	Specific Model Assumed	Electricity Demand (kWh/day)	Recommended Usable Cube (ft^3)
Supermarket	Hussmann D5X-E - 12 feet	128.57	112.68
Small Market/Convenience Store	Hussmann BCH-18	5.80	22.00
Restaurants	Delfield 6025XL-S	2.48	20.00
Home Refrigerators	None	1.23	7.28

ICF estimated refrigerant fugitive emissions based on the refrigerant used in each refrigerator type, leakage rate and annual refrigerant charge. The annual refrigerant charge is the amount of refrigerant needed in the refrigeration system in order to maintain peak operating performance. The specification sheets for the Delfield 6025XL-S and Hussmann BCH-18 models provided the refrigerant type and charge, while the Climate Conservancy 2008 report specified the refrigerant type and charge for a home refrigerator (Delfield 2013, Hussmann Corporation 2014a, Climate Conservancy 2008). The Hussmann D5X-E' refrigerant type and charge were determined through personal communications with a Hussmann service operator (Hussmann Corporation 2014b). The annual leakage rate for the Delfield 6025XL-S as well as the Hussmann BCH-18 were based on The Climate Conservancy 2008 report and confirmed using the EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2012* (The Climate Conservancy 2008, EPA 2014b). ICF estimated the annual leakage rate for the home refrigerator based on assumptions provided in EPA's 2014 GHG Inventory while the Hussmann-D5X-E's annual leakage rate was based on the information provided by the U.S. EPA's GreenChill program (EPA 2014b, EPA, 2011). Finally, the GWP factors for refrigerants used at each retail or end-use type were based on the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report for a 100-year timeframe (IPCC 2007). These assumptions are summarized in Table 8.

Table 7: Fugitive Emissions Specifications

Retail or End-Use Type	Specific Model Assumed	Refrigerant	Refrigerant Charge (kg per year)	Fugitive Emissions (% annual leakage)	GWP Emission Factor
Supermarket	Hussmann D5X-E - 12 feet	R-22	1.77	25.0%	1810
Small Market/Convenience Store	Hussmann BCH-18	R-134a	0.45	1.0%	1430
Restaurants	Delfield 6025XL-S	404a	0.40	1.0%	1100
Home Refrigerators	None	R-134a	0.16	0.6%	1430

ICF estimated the GHG emissions from the electricity consumed by the refrigerators based on the national average grid electricity mix presented in EPA's eGRID database. eGRID estimates electricity emission factors based on a reported national average grid mix of 45 percent coal, 1 percent oil, 24 percent natural gas, 20 percent nuclear, and 10 percent renewables (including hydropower, biogas, wind, solar and geothermal) (EPA 2014a). While the eGRID emission factors include GHG emissions from fuel combusted to produce electricity, they do not include the upstream emissions associated with the raw material acquisition and fuel processing. Additionally, the upstream emissions associated with the construction of power plants, manufacturing of the refrigerator, and production of the refrigerant were not included in this analysis.

5.2.2. Calculations

In order to calculate the energy and emissions associated with the refrigeration use phase, we first calculated the functional cubic volume of each beverage container type by multiplying the length, width and height of each container. Next, we calculated the quantity of beverages, by container type, that each refrigerator would contain at maximum capacity. Each commercial refrigerator's recommended usable cube (ft^3) was determined based on the interior volume, the number of shelves, and shelf size. The daily electrical demand of each commercial refrigerator was found in its respective specification sheet (Delfield Company 2013, Hussmann Corporation 2012, Hussmann Corporation 2014a).

Next, using the data gathered on refrigerator capacity as well as typical dimensions for each beverage container type, we calculated the beverage capacity of a typical refrigerator for each retail or end-use type. The refrigerator capacities for glass bottles (12 oz) in a supermarket model and the home refrigerator were based on the Climate Conservancy's report (2008). The small market/convenience store refrigerator technical specification provided an estimate of the number of 20-oz plastic bottles that would fit in the refrigerator. These data were multiplied by the ratio of functional cubic volumes of 20-oz plastic bottle to 16.9-oz plastic bottle in order to estimate the number of 16.9-oz plastic bottles that would fit.

Where data were not available to determine each refrigerator's glass bottle capacity, the ratio of each refrigerator's usable cube to the small market/convenience store refrigerator's container capacities were used. The number of beverage containers in each refrigerator can be found in Table 10.

Table 8: Refrigerator Capacity by Retail or End-Use Type and Container Type

Retail or End-Use Type	Glass Bottle Capacity (12 oz)	Aluminum Can Capacity (12 oz)	Plastic Bottle Capacity (16.9 oz)	Plastic Bottle Capacity (20 oz)
Supermarket	2,232	4,464	2,694	2,058
Small Market/Convenience Store	450	900	543	415
Restaurants	409	818	494	377
Home Refrigerators	240	360	224	171

We divided the electricity demand per day by the number of beverage containers per refrigerator, in order to calculate the electricity demand associated with one beverage container per day. This number was then divided by the volume of liquid in each container to achieve the results in kilowatt-hours per liter of beverage per day. Because a beverage was assumed to be refrigerated on average for one week, the results were multiplied by seven days to reflect the chosen time period (Climate Conservancy 2008).

Emission factors for electricity generation (EPA 2014a) were multiplied by the kilowatt-hour per liter of beverage per day quantity for each of beverage container-refrigerator combinations. Carbon dioxide, methane, and nitrous oxide emissions per liter of beverage per day were converted to grams of carbon dioxide equivalent per liter of beverage per day using the 100 year timeframe GWP factors from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report's (IPCC 2007). Refrigerant leakage rates for each refrigerator were used to calculate the fugitive emissions lost per day. These amounts were then divided by the beverage capacity of each refrigerator type and the volume of liquid in each container to determine the kilograms of CO_2e of fugitive refrigerant lost per liter of beverage over the one week refrigeration period. This was done for each combination of beverage container and retail or end-use type.

5.2.3. Energy Use and GHG Emission Results

The cumulative GHG emissions resulting from beverage refrigeration were determined by adding emissions associated with the electricity consumption to emissions from fugitive refrigerants. When cumulative energy and GHG emissions are compared across beverage container types, the 12-oz aluminum cans data show reduced energy and emissions compared to the glass 12-oz bottles and 20-oz plastic bottles. The energy results are summarized in Table 9. They reveal that aluminum 12-oz cans require 50 percent of the energy per liter of beverage needed to cool 12-oz glass bottles and 77 percent of the energy needed to cool 20-oz plastic bottles for the supermarket, small market and restaurant refrigerators. When cooled in home refrigerators, aluminum 12-oz cans require 67 percent of the energy per liter of beverage need to cool 12-oz glass bottles and 79 percent of the energy needed to cool plastic 20-oz bottles for the supermarket, small market and restaurant refrigerators. These differences in energy efficiency can be attributed to differences in space efficiency (i.e., the liters of beverage that can fit in a given refrigerator for each container type).

Table 9: Energy Use Impact by Refrigerator and Beverage Container Type

Life-Cycle Phase		Use Phase Impacts by Container Type				Aluminum Can Energy Relative to Bottles	
		Aluminum 12-oz Can	Glass 12-oz Bottle	Plastic 16.9-oz Bottle	Plastic 20-oz Bottle	Glass 12-oz Bottle vs. Aluminum Can	Plastic 20-oz Bottle vs. Aluminum Can
Refrigeration	Retail or End-Use Type	MJ/Liter of Beverage				Percent	
Electricity Demand	Supermarkets	2.04	4.09	2.41	2.66	50%	77%
	Small Markets/ Convenience Stores	0.46	0.91	0.54	0.60	50%	77%
	Restaurants	0.22	0.43	0.25	0.28	50%	77%
	Home Refrigerators	0.24	0.36	0.36	0.31	67%	79%

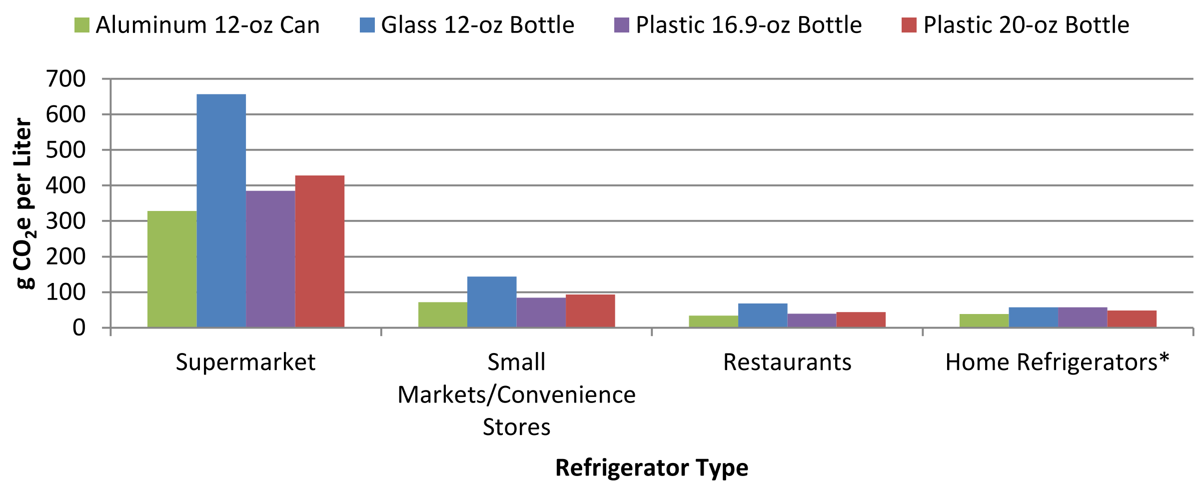
Similar trends are seen when comparing cumulative GHG emissions from beverage refrigeration across container types and retail and end-use types. As summarized in Table 10, 12-oz aluminum cans are estimated to have the lowest cumulative GHG emissions associated with the beverage refrigeration phase per liter of beverage. By comparison, over the one week refrigeration period, 12-oz glass bottles are estimated to have the cumulative highest GHG emissions per liter of beverage across all refrigerator types. Fugitive emissions are a smaller share of GHG emissions than electricity consumption, accounting for roughly 1 to 3 percent of total emissions.

Table 10: GHG Impact by Refrigerator and Beverage Container Type

Use Phase Impacts by Container Type		Source of Emissions		
		Electricity Consumption	Fugitive Refrigerants	Total
Container Type	Retail or End-Use Type	g CO_2e/L of Beverage/week refrigeration		
Aluminum 12-oz Can	Supermarkets	319.0	9.69	328.7
	Small Markets /Convenience Stores	71.4	0.39	71.8
	Restaurants	33.6	0.29	33.9
	Home Refrigerators	37.9	0.21	38.1
Glass 12-oz Bottle	Supermarkets	638.0	19.37	657.4
	Small Markets /Convenience Stores	142.8	0.78	143.5
	Restaurants	67.1	0.58	67.7
	Home Refrigerators	56.9	0.32	57.2
Plastic 20-oz Bottle	Supermarkets	415.7	12.62	428.3
	Small Markets /Convenience Stores	93.0	0.51	93.5
	Restaurants	43.7	0.38	44.1
	Home Refrigerators	48.0	0.27	48.2
Plastic 16.9-oz Bottle	Supermarkets	375.3	9.64	385.0
	Small Markets /Convenience Stores	84.0	0.39	84.4
	Restaurants	39.5	0.29	39.8
	Home Refrigerators	56.7	0.20	56.9

As shown in Figure 6, the difference in GHG emissions per liter of beverage container between container types is larger as the electricity demand of the refrigerator increases. Aluminum cans cooled in home refrigerators are estimated to have the lowest GHG burden of all container type and retail or end-use type combinations. By comparison, aluminum cans cooled in supermarket refrigerators have a much higher GHG burden due to the higher daily electricity demand. Note that the supermarket refrigerator modeled in this analysis is an open case, which is less efficient than closed case refrigerators.

Figure 5: Refrigeration Phase GHG Emissions



*Home refrigerator energy use estimates presented, although transport results do not include transport to homes, only to retail.

5.3. Combined Results

The GHG impacts presented in Table 11 combine the distribution and refrigeration emission results for beer and soft drinks by container type and per liter of beverage. The results show that aluminum cans have the lowest use-phase GHG emissions and energy demand among the container types considered.

Table 11: Total Transportation and Refrigeration Emissions and Energy Demand

Beverage, Retail or End-Use	Aluminum Cans	Glass Bottles	16.9-oz Plastic Bottles	20-oz Plastic Bottles
	GHG Emissions (g CO_2e/L)			
Beer Average				
Supermarket	400	768	NA	NA
Small Markets/ Convenience Stores	143	254	NA	NA
Restaurants	105	179	NA	NA
Home Refrigerators	109	168	NA	NA
Soft Drink Average				
Supermarket	369	720	424	468
Small Markets/ Convenience Stores	112	206	124	133
Restaurants	74	130	79	84
Home Refrigerators	78	119	96	88
	Energy Demand (MJ/L)			
Beer Average				
Supermarket	3.02	5.60	NA	NA
Small Markets/ Convenience Stores	1.43	2.43	NA	NA
Restaurants	1.19	1.94	NA	NA
Home Refrigerators	1.22	1.88	NA	NA
Soft Drink Average				
Supermarket	2.59	4.93	2.94	3.21
Small Markets/ Convenience Stores	1.00	1.76	1.08	1.14
Restaurants	0.76	1.28	0.79	0.82
Home Refrigerators	0.79	1.21	0.90	0.85

Table 12 shows the results for soft drinks in terms of 1,000 containers (rather than per liter of beverage) with soft drinks shipped to a small market/convenience store. The use-phase GHG impacts of the aluminum 12-oz cans under this scenario were estimated to be 40 kilograms of CO_2e per thousand containers of soft drinks.

Table 12: Use Phase GHG Impact for Transportation and Refrigeration of 1000 Containers of Soft Drinks

Life-Cycle Phase		Use Phase Impacts by Container Type		
		Aluminum 12-oz Can	Glass 12-oz Bottle	Plastic 20-oz Bottle
		kg CO_2e/1000 Soft Drink Containers		
Transportation	*Average*	14	22	24
Refrigeration	*Small Markets/Convenience Store*	25	51	55
Total GHG Emissions		**40**	**73**	**79**

The combined use-phase GHG emissions and energy demand are sensitive to the number of times beverages are refrigerated prior to consumption. Table 13 shows an example scenario where 1000 containers of soft drinks are refrigerated once at a small market/convenience store and again at a home refrigerator. For this scenario, the total use-phase GHG emissions increase by 34% for aluminum 12-oz cans, 28% for glass 12-oz bottles, and 36% for plastic 20-oz bottles compared to the single-refrigeration scenario presented in Table 12.

Table 13: Use Phase GHG Impact for Transportation and Two Periods of Refrigeration of 1000 Containers of Soft Drinks

Life-Cycle Phase		Use Phase Impacts by Container Type		
		Aluminum 12-oz Can	Glass 12-oz Bottle	Plastic 20-oz Bottle
		kg CO_2e/1000 Soft Drink Containers		
Transportation	*Average*	14	22	24
Refrigeration	*Small Markets/Convenience Store*	25	51	55
	Home Refrigerators	14	20	29
Total GHG Emissions		**53**	**93**	**107**

These use-phase impacts can be compared to the GHG impacts associated with aluminum can production from PE America's *Update to the Aluminum Can LCA Study* (PE Americas 2014). PE Americas estimated the GHG emissions from can production to be between 93 and 104 kilograms of CO_2e per 1,000 cans (PE Americas 2014). The use-phase GHG impact of 40 kilograms of CO_2e per 1000 aluminum cans (based on the representative scenario of beverages shipped in a large truck to a small market/convenience store) are 27 to 30 percent of the aluminum can life cycle depending on the modeling of the closed loop or recycled content approach.

The use-phase impact results can also be compared to findings from a presentation on the carbon footprint of Coca-Cola products (Coca-Cola Company 2013). Coca-Cola estimated the combined GHG emissions from the distribution and retail/vending (refrigeration) stages to be 39 kg CO_2e/1000 aluminum 12-oz cans and 74 kg CO_2e/1000 glass 12-oz bottles. Compared to the values presented in Table 12, this represents a difference of just -1% for aluminum 12-oz cans and 1% for glass 12-oz bottles.

5.4. Materials Cooling Efficiency

This subsection summarizes ICF's evaluation of the differences in beverage cooling efficiency across container types and the potential refrigeration energy use. In this analysis, ICF developed heat transfer profiles based on the different material properties of beverage container materials (aluminum, glass, and PET plastic) and the dimensions of the containers. In this subsection we describe the key assumptions that drive this assessment, describe the calculations used, and present the results.

5.4.1. Key Data Sources and Assumptions

For the purpose of evaluating the cooling rates of beverages in aluminum, glass, and plastic containers, we gathered relevant data and information from a range of sources. Much of the information needed for the refrigeration cooling rate calculations was provided in a paper by Bailey and Elban titled "Thermal Performance of Aluminum and Glass Beer Bottles" (2008). Along with providing the methodology used in this analysis, this paper identifies many geometric and material properties of glass, aluminum, water, and air.

Other key data sources include the Beverage Industry Environmental Roundtable's (BIER) *Research on the Carbon Footprint of Beer* (2012a), *Research on the Carbon Footprint of Carbonated Soft Drinks* (2012b)*,* and the project report submitted to the Faculty of the Worcester Polytechnic Institute titled *Glass and Aluminum Beverage Bottle Comparison* (Shevlin and Soffen 2009). The BIER carbon footprint reports provide key inputs on "chill to" temperature, storage time in supermarkets and liquor stores, and refrigerant and leakage rates used in this analysis. The report by Shevlin and Soffen (2009) built on the methodology in Bailey and Elban (2008) and described a model written with the COMSOL program to provide a visual representation of how the heat transfer mechanisms affect the cooling of bottles. Bailey and Elban (2008) was also used to double-check the calculations performed in this analysis.

ICF developed the following assumptions from the data gathered during the literature review:

- Beverage containers were assumed to be cylindrical for mathematical simplicity to estimate surface area and volume.
- A simple steady-state equation, which estimates the total heat transferred without respect to time, was solved to estimate cooling behavior of beverages in containers. More accurate estimates of the cooling behavior of beverages would require finite element modeling various container types with precise dimensions to account for the many factors affecting the rate at which the containers are cooled.
- The cooling behavior of multiple bottles in the refrigerator was not estimated due to mathematical complexity.
- For cooling profile calculations, the ambient temperature of the inside of the refrigerator was held constant without taking into account actual working conditions of the refrigerator, the frequency of operation of the compressor, the power of the refrigerator, and other variations in refrigerator type.
- For energy consumption estimation, the typical energy consumption of various refrigerators was gathered from relevant literature.

5.4.2. Calculations and Parameters

A steady state equation was used to determine the total heat transfer between the containers and the refrigerator. This, along with the relationship between total heat transferred and the heat transfer coefficient were used to approximate the rate of cooling beverage containers from an initial temperature of 300 K (80.33°F) to an equilibrium temperature of 275 K (35.33°F). The equilibrium temperature was chosen based on the recommended chill-to temperature for beverages modeled in this analysis provided in the BIER carbon footprint studies (BIER 2012a, BIER 2012b).

The material properties for glass and aluminum bottles as well as material properties of air and water (the working fluid) were taken from Bailey and Elban (2008). Properties for PET bottles were obtained from Esterform packaging (Esterform 2013). The thickness of the PET bottle was obtained from KenPlas Moulding (Kenplas 2013). For this analysis, two comparisons of cooling profiles for aluminum, glass, and PET beverage containers were performed:

i) Using a set of constant cylinder dimensions to model all three types of beverage containers; and
ii) Using cylinder dimensions for each container type based on their actual shapes.

In the first comparison, the geometric parameters of containers were chosen such that the inner diameter was held constant at 6 cm and the volume was held constant at 355 ml. Because the main driving factor for the cooling of the liquid in the containers is the total volume of the liquid, assuming a constant volume of liquid across container types enabled ICF to better understand the material performance of aluminum as it compared with glass and PET irrespective of differences in diameter, height and volume of different containers. The parameters used in this comparison are shown in Table 14.

Table 14: Assumed geometric parameters for comparing cooling behavior assuming similar geometric dimensions

Geometric Parameters				
Parameter	Unit	Value		
		Glass container	Aluminum container	PET container
Outer Diameter, d_0	m	6.71E-02	6.14E-02	6.06E-02
Wall Thickness, L	m	3.56E-03	7.11E-04	3.15E-04
Inner Diameter	m	6.00E-02	6.00E-02	6.00E-02
Height of Liquid in bottle, H	m	0.1256	0.1256	0.1256
Bottle (Effective) Surface Area, A_i	m^2	0.0265	0.0242	0.0239
Volume, V_L	m^3	3.55E-04	3.55E-04	3.55E-04

In the next analysis, actual geometric parameters were approximated using various data sources. The glass bottle dimensions were chosen from a commercial glass bottle selling company, Owens Illinois, Body code 500021 (Owens Illinois 2012). The aluminum can dimensions were drawn from the standard 330-ml can design provided by REXAM (Rexam 2013), a commercial can-making company. For both the aluminum and glass containers, the outer diameter was taken from the specifications and the thickness was obtained from Bailey and Elban (2008). These values were used to calculate the inner diameter of the cylinder. The height of the cylinder used to model each container was then approximated such that the volume was close to 355 ml. The PET bottle dimensions were obtained from Esterform packaging (Esterform 2013) and a similar method was used to approximate a working cylinder. The geometric parameters are summarized in Table 15.

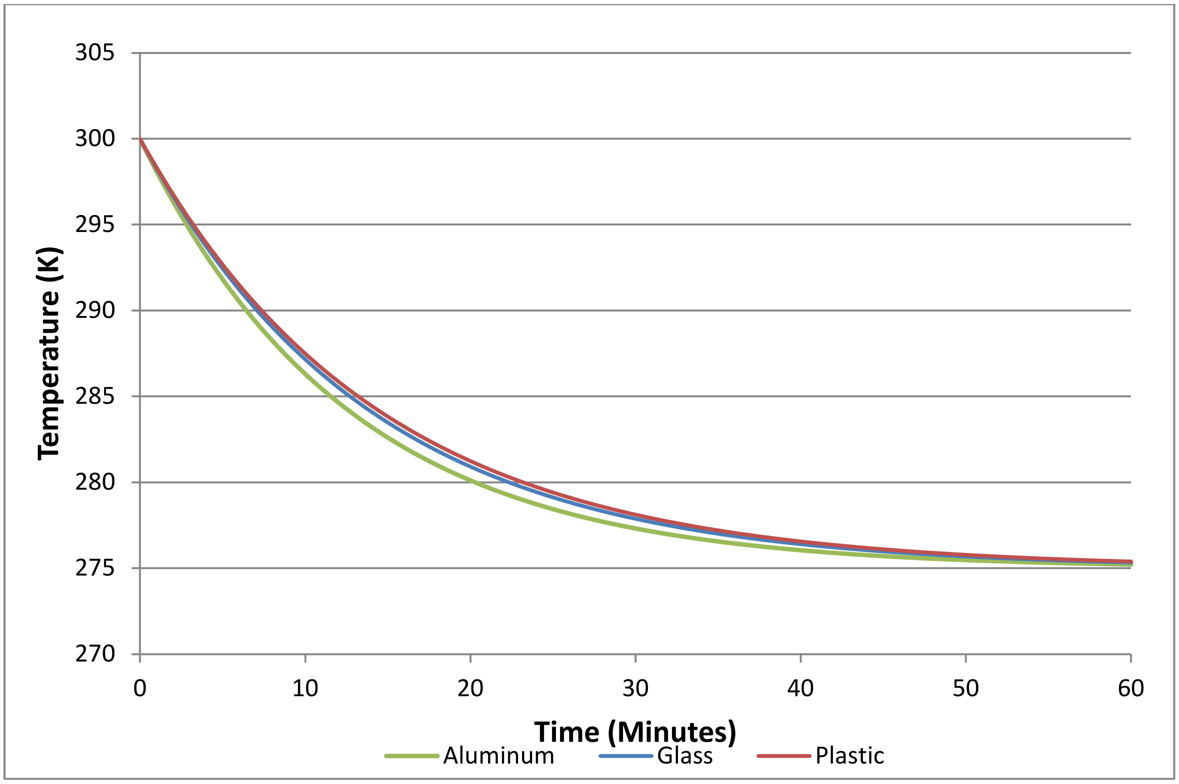
Table 15: Assumed geometric parameters for comparing cooling behavior assuming actual geometric dimensions

Geometric Parameters				
Parameter	Unit	Value		
		Glass bottle	Aluminum can	PET bottle
Outer Diameter, d_0	m	6.10E-02	6.63E-02	6.20E-02
Wall Thickness, L	m	3.56E-03	7.11E-04	3.15E-04
Inner Diameter	m	5.38E-02	6.49E-02	6.14E-02
Height of Liquid in bottle, H	m	0.1559	0.1071	0.1195
Bottle (Effective) Surface Area, A_i	m^2	0.0299	0.0223	0.0233
Volume, V_L	m^3	3.55E-04	3.54E-04	3.53E-04

5.4.3. Results and Discussion

The refrigeration efficiency calculations showed that, for similar dimensions of containers, the beverages cool fastest in the aluminum can, followed by glass and then PET. The heat transfer through these container materials was found to be driven primarily by two factors: the thermal conductivity of the materials used and the external surface area of the container. Aluminum performed better than both glass and PET containers due its high conductivity—the ability to transfer heat. Glass bottles performed slightly better than PET bottles because of a larger external surface area[6] despite having a lower conductivity than PET. The results of the comparison are shown in Figure 7.

Figure 6: Cooling Profile of Water in Uniform Beverage Container Dimensions in a Refrigerator at 275 K (35° F)



For containers close to the actual dimensions of 12-oz aluminum cans, 12-oz glass bottles, and 16.9-oz PET bottles, it was observed that the glass containers cooled the fastest, followed by aluminum and PET bottles. This was a result of a larger outside surface area of a glass bottle, which is taller than aluminum cans and bottles. The higher heat transfer resulting from a larger surface area of glass bottles offset the lower heat transfer resulting from the lower thermal conductivity of glass, resulting in net higher heat transfer rate compared to both aluminum cans and PET bottles. Aluminum performed better than PET bottles because of the higher thermal conductivity despite having lower external surface area. The results of the comparison are shown in Figure 7.

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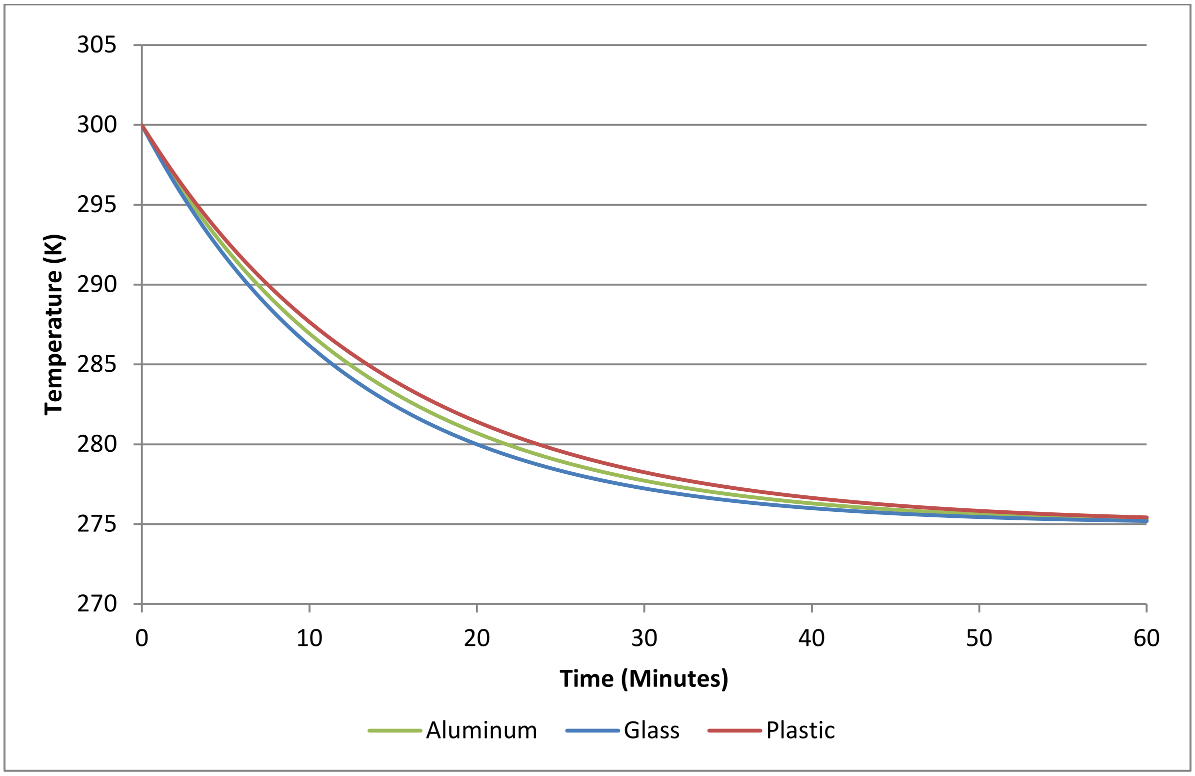
[6] The internal areas of all the containers were kept constant. However, the greater thickness of the glass bottle caused the external area to be larger.

Figure 7: Cooling Profile of Water in Approximated Beverage Container Dimensions in a Refrigerator at 275 K (35° F)



In a scenario where beverages were left in the refrigerator long enough to reach the internal ambient temperature, all containers reached that temperature at approximately same amount of time, showing no discernible advantage of one container over other under practical beverage consumption or turnover practices. However, in scenarios where chill-to temperature is higher than the ambient temperature of the refrigerator and assuming approximated container dimensions, the glass bottles reached that temperature fastest. Therefore, in a scenario with quick turn-over rates (i.e., beverages taken out of the refrigerators before reaching the chill-to temperature), the beverages contained in glass bottles would be the coldest.

5.5. Potential Distribution Impacts at National Scale

This section examines the potential GHG emission impacts of distribution based on the annual quantities of beverages contained in aluminum cans and distributed in the United States. This analysis is intended to help illustrate the magnitude of the potential impacts investigated in this study.

For this effort, ICF gathered available data on annual U.S. shipments of beverages. The Aluminum Association estimated that 94 billion aluminum cans were shipped in recent years, of which 60 percent contained non-alcoholic beverages (soda and energy drinks) and 40 percent contained beer (The Aluminum Association 2015). Assuming average distribution assumptions, emissions from distributing beverages in aluminum cans totaled about 1.75 million MTCO$_2$e in 2014. Beer- and soft drink-related transport emissions accounted for 54 and 46 percent, respectively, of those emissions. Increasing space efficiency during distribution offers opportunities to decrease emissions from this stage of the beverage life cycle. Estimating national-level emissions for the other container types was limited by the available data sources (e.g., data on sales and shipments covered different years, beer and soft drink data were reported from different sources, which could make for a less even comparison).

We were unable to locate a source with information on the shares of packaged soft drinks and beer sold to different retail locations on average at the national level to appropriately estimate refrigeration emission impacts at the national scale.[7] Further sensitivity analyses could be performed in regards to the annual sales volumes by beverage type and by distribution markets in order to understand the national scale impact of these beverage container use-phase emissions.

6. Data Gaps, Limitations, and Future Research Areas

This section provides a summary of the main data gaps encountered in the course of this analysis, limitations, and areas where further research is needed.

6.1. Distribution

A few key data gaps and limitations associated with the transport of carbonated beverages may warrant further investigation in the future. These included:

(1) The proportion of carbonated beverages refrigerated during transport; and

(2) The relative distribution of soft drink delivery vehicles by size and stage (manufacturing to wholesale and wholesale to retail) their role in the distribution network.

For each of these areas, data were unavailable or limited by the wide variety of beverages on the market in the United States and the lack of uniform, aggregated data characterizing their distribution.

Refrigeration during transport: The share of carbonated beverages that are refrigerated during transportation was not quantified during the literature review, although communications with two beverage industry stakeholders indicated that refrigerated transport was used for a minority of carbonated beverages transported in the United States (Thompson 2013, Brooks 2013). Therefore, the energy and GHG emission impacts from refrigerated transport were not factored into the transport analysis. One study indicated that distribution in refrigerated vehicles increased fuel consumption by approximately 20 percent (Lalonde et al. 2013).

Distribution of soft drinks by truck size and stage: As demonstrated in Section 5.1.3, there is significant variation in the efficiency and emissions produced by the different sizes of beverage delivery trucks included in this analysis. However, disaggregated data describing the roles of each size of truck within the beverage distribution network were lacking. The analysis assumed that larger trucks are likely used to haul beverages long distances, with smaller trucks used solely for “last mile”, local deliveries. In this analysis, ICF assumed that the entirety of the distance that soft drink beverages were shipped was traveled by large trucks, as the long-distance travel was likely the largest share of the overall distance traveled.

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[7] One study indicated that an estimated 30 percent of Fat Tire beer is sold to supermarkets (The Climate Conservancy 2008); however, this study did not provide information on other sales channels and is specific to this beer product.

6.2. Refrigeration

A few key areas of uncertainty in regards to the refrigeration analysis may also warrant further investigation. These included:

(1) The amount of time beverages are stored in refrigerators at different retail or end-use locations;

(2) Actual refrigerator loading and storing practices by retail location and container type; and

(3) Refrigerator types by retail location;

(4) National-level data on the volume of beverages sold and refrigerated at different retail or end-use locations by container type.

For each of these areas, some data were publicly available; however, more robust data would improve the analysis.

Cooling period: In the refrigeration GHG calculations, it was assumed that each beverage container remained in the refrigerator for one week (The Climate Conservancy 2008). ICF recognizes that, in practice, the cooling time for each beverage will depend on the retail or end-use type, beverage type, container type, and other factors dictated by the specific market conditions (e.g., geography, time of day, time of year). Some stores may stock their refrigerators daily to match a high level of turnover, whereas a restaurant may not have the same rate of turnover. More robust data, if available, on rates of beverage turnover would allow this analysis to better reflect the impacts from specific retail or end-use locations and beverage container types.

Actual refrigerator loading and storing practices: This analysis assumed that refrigeration space is optimized (i.e., refrigerators are fully loaded to capacity), but this may not always be the case in practice. Further information on actual filling practices and turnover rates and how they may vary by retail type and possibly by container type would help refine the analysis.

Refrigerator types*:* In this analysis, a single refrigerator model was evaluated for each retail location. Further analysis would benefit from a study of a range of refrigerator types used in practice, and in particular, examining the impacts of closed versus open-door refrigeration at supermarkets.

National beverage sales by location and container type**:** Information about annual retail sales by container type was not available in one central location; annual retail sales data were therefore gathered from separate sources specific to each container type, acknowledging that national beverage sales data vary in year and boundaries. ICF sought to gather data on the share of packaged beverage sales to different retail locations in order to understand the national scale impact of the beverage container use-phase emissions; however, this information was not located. The share of beverage sales to supermarket versus convenience stores or restaurants that are in turn refrigerated would have a significant impact on the overall GHG emissions picture for the beverage use phase given that supermarket refrigeration was found to be most energy and GHG-intensive.

6.3. Overall

In general, sensitivity analyses on specific factors or assumptions used in the analysis would be a useful future work area to evaluate the effect of different factors on the results. In the calculation spreadsheet developed for this analysis, key inputs could be varied and tested including transport distance, truck size truck pallet capacity, refrigeration time, refrigeration capacity, and refrigerator type and energy use to investigate the sensitivity of the results to changes in assumptions and inputs.

7. Summary of Conclusions

Overall, this analysis showed that space efficiencies offered by beverage container dimensions in both transportation vehicles and in refrigerators allow for less fuel and electricity use and lower GHG emissions. Specifically, in the respective container use phases, this study found the following:

- In the distribution phase,
    - Space efficiency and lower packaging weight during transportation allowed for approximately 35 percent lower GHG emissions for aluminum cans compared to glass bottles per liter of beverage transported.
    - Plastic bottles showed similar transportation emissions impacts as aluminum cans.

- In the refrigeration phase,
    - Space efficiency during beverage cooling allowed for lower GHG emissions for aluminum cans compared to both glass bottles and plastic bottles.
    - The largest GHG emissions savings from aluminum cans compared to other containers were seen in supermarket refrigerators.
    - Differences were negligible in the cooling efficiency of aluminum, glass, and plastic containers based on material properties.

On-pallet space and mass efficiency served as the key driver for energy and GHG emissions savings in the transportation phase. Refrigerator energy consumption and space efficiency were the key drivers for energy and GHG emissions in the refrigeration phase.

The distribution and refrigeration of beverages in aluminum cans was found to represent a significant share of the aluminum can life-cycle emissions: in a combined distribution and refrigeration scenario of transport of soft drinks packaged in aluminum cans to a small market/convenience store (presented in Section 5.3), emissions for the distribution and refrigeration phases represent about 25 percent of the aluminum can life-cycle GHG emissions. Distribution accounted for 36 percent of those emissions and refrigeration accounted for the remaining 64 percent.

These findings indicate that practices during these life phases, and in particular during the retail refrigeration phase, are meaningful in terms of influencing the life-cycle GHG impacts of beverage containers. This suggests the need for further investigation of some of the data gaps and of opportunities to increase efficiencies during these life phases.

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Appendix A: Container Illustrations

Illustration approximations of the container types considered in this analysis with notes on the cylinder dimensions are provided below.

Aluminum Can Approximation Illustration

330ml Standard

Approximate cylinder dimensions, assumed to hold 12 fl. oz

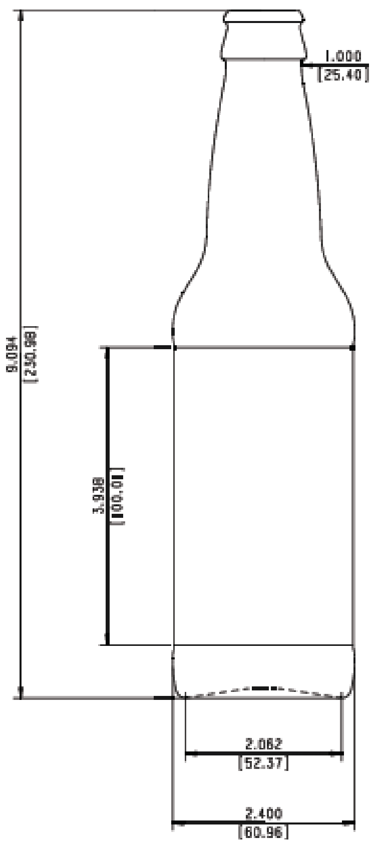
Note: this can is specified to hold 330 ml, which includes empty space on top. Calculations show that with these dimensions the can will hold 355 ml.

End Use	Beverage - Beer, Beverage - CSD & Water, Beverage - Energy Drinks, Beverage - Fruit Juices, Beverage - Spirits

Pack Type	Can
Specification Notes	Can also be used with a 206 diameter end (57mm).
Height	115.2 mm [Metric]
End Diameter	52 mm [Metric]
Volume	330 ml [Metric]
Body Diameter	66.3 mm [Metric]
Metal type	Metal - Aluminium

Source: Rexam 2013.

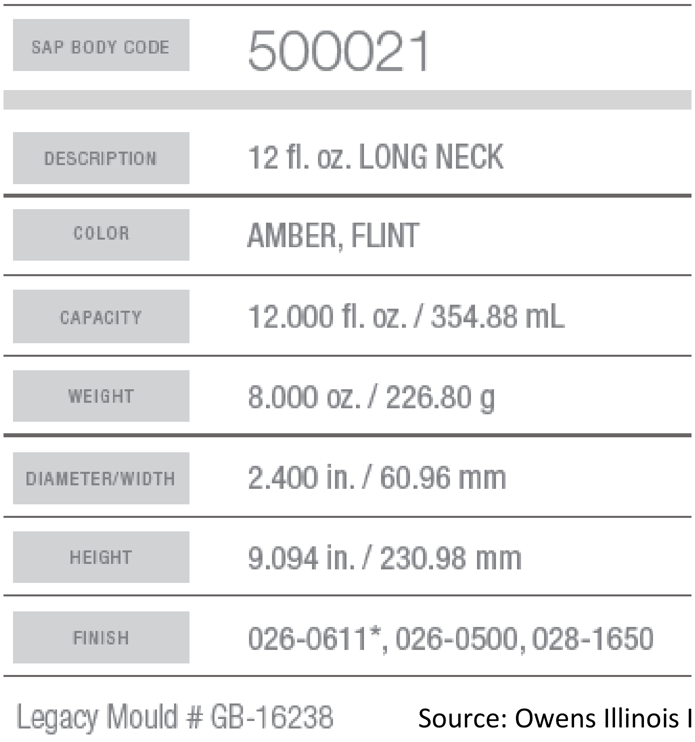
Bottle Approximation Illustration



155.9 mm

60.96 mm
Thickness:
3.56 mm
ID: 53.84mm

Approximate cylinder dimensions, assumed to hold 12 fl. oz

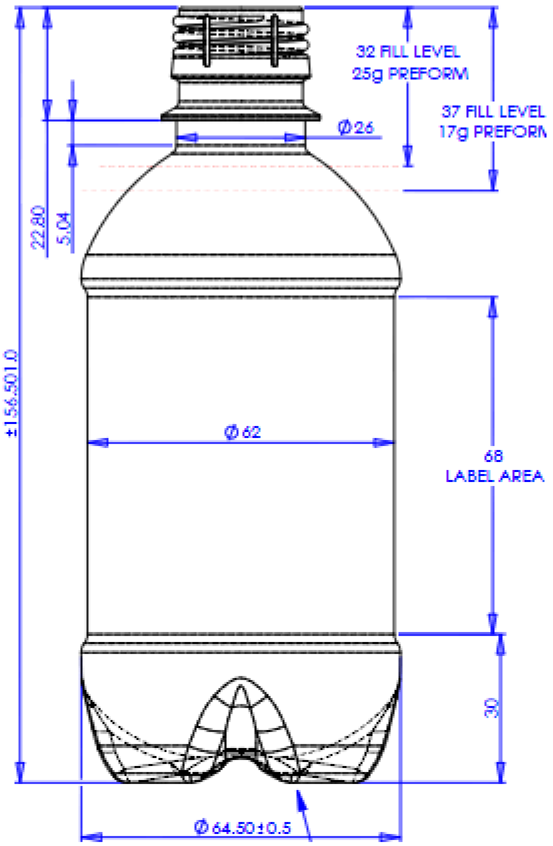


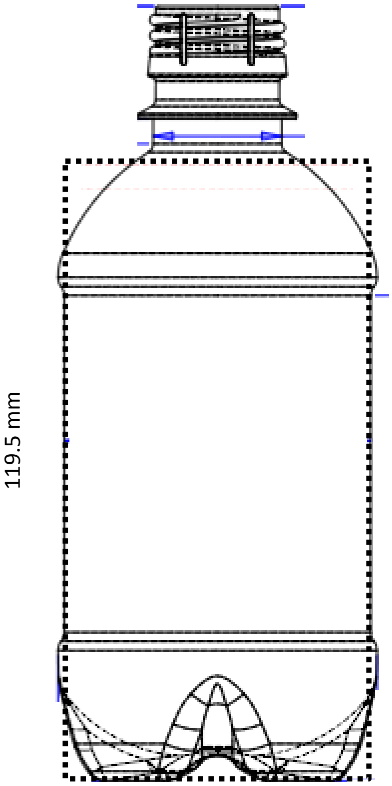
SAP BODY CODE	500021
DESCRIPTION	12 fl. oz. LONG NECK
COLOR	AMBER, FLINT
CAPACITY	12.000 fl. oz. / 354.88 mL
WEIGHT	8.000 oz. / 226.80 g
DIAMETER/WIDTH	2.400 in. / 60.96 mm
HEIGHT	9.094 in. / 230.98 mm
FINISH	026-0611*, 026-0500, 028-1650

Legacy Mould # GB-16238

Source: Owens Illinois Inc. 2012.

PET Bottle Approximation Illustration





Approximate cylinder dimensions, assumed to hold 12 fl. oz

Note: the extra volume in the diagram is responsible for holding extra liquid storage since the bottle is 330 ml and our calculation is for a 355-ml bottle.

Source: Esterform Packaging 2013.