Assessing the Environmental Impact of Automotive Recyclers of Massachusetts

A Major Qualifying Project

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By:

Muhammad Siddiq, ME
Richard Coffin, ME
Matthew Puksta, ME
Aimilios Tachiaos, ME

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Approved By:

Professor Brajendra Mishra, Project Advisor

Abstract

This project was focused on the automotive recycling industry in Massachusetts. The study was sponsored by the Automotive Recyclers of Massachusetts (ARM). The goals of this study were to understand how much material is recovered, reused, and recycled and how these activities impact the state's carbon footprint. The report includes the understanding of how environmental hazards, such as waste oil, are processed. The primary method of data collection comprised of site visits for collecting information on number of cars processed, the type and volume of parts recovered and the amount of hazardous materials that are safely processed. The difference in carbon footprint between processing recycled materials and using primary raw materials have been analyzed. A survey of the members of ARM was conducted. The primary method of data analysis is through the use of 'Sustainable Minds' - a software program used to calculate the carbon footprint of the process involved. The study has determined that for this specific industry, the carbon footprint is significantly negative, however it is recommended that this study be furthered to include processes, such as shredding, smelting and casting.

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Members of the Automotive Recyclers of Massachusetts

Executive Summary

This project was sponsored by the Automotive Recyclers of Massachusetts (ARM) with the goal of assessing the environmental impact of recyclers in the state of Mass. The team was tasked with quantifying the number of vehicles, types of parts sold, types of hazardous waste and the overall amount of carbon saved by recycling. The team started with a literature review of the industry. Due to a lack of source material about the metal compositions of parts and the cost of mining, refining, and producing the metal the team had to calculate those numbers themselves. The team calculated the total amount of metal required to produce the 2015 domestic car production. This was done by using a variety of sources to accurately approximate the fuel and energy cost of mining. The smelting cost for refining of raw and scrap metal. And the production cost to assemble all of the cars. The final number was given as a range due to a variance in the refining process. Refining can take many different forms and techniques and can ultimately take different amounts of energy. The key point to understand in this portion of the process is the massive reduction in energy required to refine scrap instead of virgin metal. The third process is the general production of the cars. This was done by using the largest factory in America and approximating the cost to produce all the cars at that facility. All of the fuel and kWh were then converted to carbon tons using the EPA free software. The final answer being between 78,095,147 and 158,623,481 tons of carbon.

The second step in the process was to acquire information of the industry and operations. This was done via surveys and site visits. The team visited several ARM facilities in order to understand the operations through observation and through conversation with the owners. The second portion was a survey sent to the ARM to acquire data from other members for later usage. This data helped answer questions about the overall system of operations and how many cars and parts were processed in Massachusetts. This data was processed in two ways. As a range of answers due to the wide variance in responses due to differences in size, employees, and business models. Second it was averaged due to the request of the ARM for an averaged answer.

The results of the data and four questions by the ARM were answered accordingly. The number of vehicles scrapped in Massachusetts is approximately 165,500. This was done by averaging the number of cars processed annually by each operation and multiplying it by the total number of ARM members in the state.

Second the variance of parts sold in Massachusetts was calculated by surveying the top sellers at each facility. The common parts that appeared in almost every survey were: wheels, doors, engines, transmission, tail lights and mirrors. These parts were then counted and following the same method as part one were averaged to approximate the yearly sales of each part.

Third was the classification and disposal methods of hazardous chemicals. The team found all facilities in compliance with state regulations and that each facility was wisely disposing of materials. They were selling antifreeze and refrigerants, using the gasoline, and burning excess oils.

Fourth was the environmental impact of recycling. The team used the calculations in the background and with the answer to question one for total cars to tabulate the amount of metal. The carbon cost per ton was then calculate for virgin and scrap tons. The difference between the

two was the amount of savings in tons of carbon per year for the ARM, which was approximately 2.7 million tons a year.

Using the information provided for the most common parts, the project team asses the carbon footprint of the production of these parts using the software Sustainable Minds. This was done by creating a bill of materials for each part and the process required to create those parts. The software provided was with the equivalent amount of carbon dioxide in kilograms required to produce a single part from virgin materials. The analysis consisted of four items, which were the transmission, engine, alloy wheels, and tires. The production of these parts creates 921 kg, 1620 kg, 109 kg, and 36.6 kg of carbon dioxide respectively. From these results it can be noted that the largest positive impact to the environment are made by reusing transmissions and engines. Considering the large number of wheels and tires that are recycled, the comparatively small savings are not negligible.

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1. Introduction

The automotive industry is one of the largest industries in the world. The quantity of vehicles produced around the world is exceedingly high, with 73 million cars being made worldwide in 2007 (Vermeluen et al, 2007). Furthermore, every vehicle that is produced requires the use of a diverse number of materials. The extraction and processing of these materials leaves a considerable footprint on the environment.

Automotive recycling is a large industry in the United States. It is reported that nearly all cars are recycled at the end of their life. ("Steel Markets: Automotive"). It is a step in the life cycle of automotive industry. Typically, a car is created from virgin material which has been processed from ore and has not been used for any other purpose prior to its use in a car. Once the vehicle reaches the end of its life, it is considered scrap. If not disposed of appropriately, the vehicle and its parts will end up in landfills. Because of the materials and processes these materials go through, the materials are not able to breakdown efficiently in the landfills. The automotive recycling industry provides an outlet where parts of the vehicle are not sent to landfills, but instead repurposed in one of a few ways.

This means that parts of an unwanted car can be reused through the sale of parts that are in working order as replacements. Within this context it may be understood that these parts are recycled since they do not require the production of a new part because the part has already been manufactured. Instead, the part is simply being resold to a new customer. The benefits purported by the industry are that purchasing parts from a recycler are beneficial to the environment and it is a viably cheaper option for the consumer.

In order for the vehicle to be, in effect, be recycled, there are dismantlers which take apart the vehicle. The following project is sponsored by the Automotive Recyclers of Massachusetts (ARM). The ARM is a non-profit organization that is comprised of 60 members and 9 associate members located in the state of Massachusetts. The members of the ARM are facilities that take in the vehicles dismantle the parts from the vehicles and provide a venue for the sale of used parts.

The overall objective of this project was to provide a better understanding of the automotive recycling industry in Massachusetts. For the purposes of this project, the only considered materials were metals used in vehicles. This was done considering the largest percentage weight in a vehicle came from metals, and no other materials such as fabrics, glass, and plastics. The ARM commissioned this project with a few objectives to better understand their business. These objectives were to: quantify the number of vehicles taken into these facilities, define the diversity of parts salvaged, record the amounts of hazardous materials and how they are disposed, and to determine what environmental benefits, if any, are yielded by these recycling facilities with respect to producing new materials.

2. Background

2.1 Important Terms

All definitions within quotations were obtained from an online dictionary, Dictionary.com

Ore: "a metal-bearing mineral or rock, or a native metal that can be mined at a profit." In regards to this paper ore refers to all material removed from the ground with intention to be refined for metal production

Refining: "to bring to a fine or a pure state; free from impurities" Refining refers to the process of smelting ore to reform it into new materials such as aluminum or steel

Smelting: the process of reducing an ore to a relatively pure metal, typically through heating. The process by which a material is refined

Mines: "an excavation made in the earth for the purpose of extracting ores, coal, precious stones, etc." Frequently referring to large open pit mines where common ores such as iron ore is extracted. Open pit mines are the largest such mines and are common in mining countries

Factory: "a building or group of buildings with facilities for the manufacture of goods." Refers to the production centers of major automobile manufactures where raw materials are converted into vehicles

Iron: "a ductile, malleable, silver-white metallic element, scarcely known in a pure condition, but much used in its crude or impure carbon-containing forms for making tools, implements, machinery" Iron in this paper refers to the material of refined and processed iron made from ore for industrial purposes

Steel: "any of various modified forms of iron, artificially produced, having a carbon content less than that of pig iron and more than that of wrought iron, and having qualities of hardness, elasticity, and strength varying according to composition and heat treatment: generally categorized as having a high, medium, or low-carbon content." For the purpose of this paper steel is defined as the most common material in automobiles and the grade of carbon does not matter

Aluminum: "a silver-white metallic element, light in weight, ductile, malleable, and not readily corroded or tarnished, occurring combined in nature in igneous rock, shale, clay, and most soil: used in alloys and for lightweight utensils, castings, airplane parts" Aluminum is defined as a light weight material made from bauxite ore. The grade or type of aluminum is not considered relevant for this paper

Bauxite: "a rock consisting of aluminum oxides and hydroxides with various impurities: the principal ore of aluminum." Bauxite is the general ore from which aluminum is produced

Carbon Footprint: “the amount of carbon dioxide or other carbon compounds emitted into the atmosphere by the activities of an individual, company, country, etc.” This paper uses carbon footprint to define the environmental cost of all smelting, mining, refining, and burning of fossil fuels in the production of materials and products

Tonne: The non-American ton has a conversion ratio 1:1.1 for tonne to ton. A tonne is also known as a metric ton

Ton: The America ton defined as 2000 pounds

Kilogram: “a unit of mass equal to 1000 grams: the basic unit of mass in the International System of Units (SI), equal to the mass of the international prototype of the kilogram, a platinum-iridium cylinder kept in Sèvres, France” The nonstandard unit of mass in this paper. Kilograms will be converted to pounds using the ratio of 1 lbs: 0.45kg

Car: This paper refers to all personnel vehicles from compact cars through trucks as cars. As is stated later on the average “car” in this paper is the midsize vehicle in terms of weight and size

Ingots: “A mass of metal cast in a convenient form for shaping, re-melting, or refining” For the purpose of this paper refined metals come in two types of forms Ingots and Sheet Metal

Sheet metal: “metal in sheets or thin plates” For the purpose of this paper refined metals come in two types of forms Ingots and Sheet Metal

Composites: “made up of disparate or separate parts or elements; compound” In terms of this paper composites refer to either composite metals, plastics, or fabrics. Composites refers to any material that is not purely one substance, i.e. steel is a composite metal

Plastics: “any of a group of synthetic or natural organic materials that may be shaped when soft and then hardened, including many types of resins, polymers, cellulose derivatives, casein materials, and proteins: used in place of other materials, as glass, wood, and metals, in construction and decoration, for making many articles, as coatings, and, drawn into filaments, for weaving.” Plastics in this paper refers to a wide assortment of materials including synthetic fibers like nylon, hard plastic surfaces, and any non metal non organic material found in the vehicles

Recycled Metals: In terms of this paper recycled metal refers to any metal that has been refined using scrap metal of the same kind

Scrap Metal: “discarded metal for reprocessing” Any metal that has already been used at least once and is intended for re-smelting to be reformed into Recycled Metal

Crush: A crush refers to a crushed flattened vehicle that will then be shipped as bulk weight for recycling

ARM: Automotive Recyclers of Massachusetts

The American auto industry began in 1893 with the Duryea automobile. Built in Massachusetts the vehicle made its debut in Springfield Mass in 1893, the vehicle achieved an average speed of seven and a half miles per hour. The first true American car maker would arrive in 1901 with Henry Ford. His famous Model A and Model T were the first vehicles built for the common man. Sporting a reasonable asking price, the Model T sold over 10,000 in its first year on the market. Ford would soon build the largest automotive plant of its time the Highland Park Michigan Plant. The plant produced some 300,000 cars in 1914 (Hughes, 1989). Some 101 years later the automotive industry would produce 12 million new vehicles domestically alone. The question that now faces the industry is: what to do with over 100 years of older vehicles? The immense amount of material alone is staggering, but it is the unforeseen cost to the environment that is most concerning. As the industry expands, so must recycling operations to reclaim old metals for future use. Consider how much iron or steel is required for the production of 12 million vehicles, but how much energy is that? What is the true cost to mine, refine, and produce all that metal and then fashion it into vehicles? This paper will seek to investigate the overall cost of the domestic automotive industry's carbon footprint along with Massachusetts' attempt to reduce that carbon through recycling operations. This paper will identify the rough cost to the environment for the domestic production of 2015 and then estimate the total amount of energy and carbon saved by diligent recycling methods practiced at numerous recycling facilities throughout Massachusetts.

First a general understanding of the process of material harvesting and refining must be defined. The majority of this paper will focus on the metals used in a car as these are the most frequently and easily recycled; and because a car is overwhelmingly metal in composition, at around 75% by mass (Select USA). The majority of material required for this process, bauxite ore and iron ore are mined in open pit mines. Open pit mines are large holes in the earth's surface that are characterized by their spiraling roads down to the bottom of the mine. The mines are generally massive and excavate the absolute maximum amount of material when compared to a traditional mine. A traditional mine or mine shaft typically follows a vein of ore through the earth's crust and tries to avoid the collection of excess material, called overburden. Open pit mines however embrace overburden. They excavate a massive area that has any chance of including the ore or material that the company is seeking. When chasing large deposits of relatively common materials in high demand, such as iron ore or bauxite, this is generally considered the best way to mine. (The New Steel)

The next phase of the operation is refining. Metals are typically refined by heating the ore in a crucible to reduce the ore to molten metal and remove impurities. This process is known as smelting. This process differs based on the raw ore used and the metal or alloy to be produced. All metals have different melting points and more importantly certain metals like steel are not made from pure ore. Refining iron ore or bauxite will produce iron or aluminum respectively. Steel production however requires large amounts of both limestone and iron in order to be produced.

The final phase of the operation is to process the metal into the various car parts. Most metals are initially formed as either sheet metal or ingots. This metal will need to be processed through several means, such as melting prior to forming a casting or forming of sheet metal, to yield the necessary components. This process frequently requires additional metals to be added to form alloys.

The United States Automotive Industry is among the largest manufacturing based economic forces in the world. Counting both production and sale of vehicles, the United States is the largest market behind only the People's Republic of China. Between 2009 and 2015 the United States Automotive Industry has doubled in production, at 6 million in 2009 and as of 2015 12 million passenger vehicles. Sales have also increased, going from 10.4 million in 2009, to 17.4 million in 2015. The domestic automotive industry, accounting for; sales, production, and dealerships; was 3.5 % of Gross Domestic Production in 2015. That equates to roughly 910,000 jobs in 2015 (Select USA).

The sheer size of the industry and its production means that its production is of equal magnitude. First assume that a car is approximately 60% steel by weight and that the average midsize car is approximately 3500 pounds. Next, assume that a midsized car represents the median of the 12 million passenger vehicles produced in 2015, which includes sedans, compact cars, large cars, trucks and SUVs. It then follows that there is 2100 pounds of steel in a car, which is 60% of the total weight of 3500 pounds. Also, the average mixture for steel used in America is 75% steel from virgin iron, or virgin steel, and 25% reclaimed steel made from recycled steel. Additionally, producing a ton of virgin steel from ore requires "2500 pounds of iron ore, 1400 pounds of coal and 120 pounds of limestone." (Steel Markets: Automotive)

Based on the previously stated assumptions, the 2100 pounds of steel in a midsized car is comprised of 1575 pounds of virgin steel and 525 pounds of reclaimed steel. When these values are multiplied by 2015's 12 million domestic manufacturing orders, it equates to 18.9 billion pounds of virgin steel, or 9.45 million tons, and 3.15 million tons of reclaimed steel. Since producing a ton of virgin steel requires 2500 pounds of iron ore, 1400 pounds of coal and 120 pounds of limestone, producing the 9.45 million tons of virgin steel in cars requires 23.6 billion pounds of iron ore, 13.2 billion pounds of coal, and 1.13 billion pounds of limestone. It warrants repeating that this represents only the production of steel in 2015 for America alone. In other words, this is only the estimation for 60% of the cars and the amount of material is already astronomical (Steel: The EnviroMetal).

All of this serves one purpose: to underscore the importance of proper waste reduction through recycling. Without even considering the energy cost of mining, transporting, and refining virgin steel, it is still evident from simply the magnitude of material needed for producing cars that proper automotive recycling can have an enormous benefit to the environment.

2.2 Composition and Energy Cost

Due to the rise of composite materials, it has become increasing difficult to approximate the individual material composition of individual components. This difficulty is compounded by the fact that the majority of the car is made of specific alloys, which vary widely and are not public knowledge due to the competitive nature of the industry. Due to these considerations, the scope of this report will consider cars as a whole because it is more readily known how much metal is in a car overall. According to data from TMS the average car contains 60% steel, 8% aluminum, and 6.4% cast iron (Kanari, Pineau, and Shallari, 2003).

These metals, along with other assorted metals such as zinc, copper lead, platinum, and magnesium, make up 76.4% of the vehicle. The remaining portion of the vehicle are plastics, rubber, and miscellaneous components such as adhesives, glass, and fluids. Since the significant majority of the mass of a car in made out of metal, the majority of the energy cost to produce the vehicle will be in the cost of metal manufacturing.

2.3 Mining Estimations

Ore extracting and the process of mining is an incredibly high energy operation. As stated earlier, the production of virgin steel requires iron, limestone, and coal primarily. For the purpose of this paper, producing steel will only require these three materials. First the mining of iron ore will be considered. The majority of iron ore is mined in the Australian continent, which contains seven of the world's largest mines for iron ore. This is partly fueled by the demand of the Chinese economy, which contributes 60% of the global iron consumption. The largest of these mines the Rio Tinto mine in Australia which is also known as Hamersley. This mine produces approximately 163 million metric tons a year, or 180 million US tons a year (True Giants of Mining). Now consider the 23.6 billion pounds, or 11.81 million tons, of required iron. The industry standard open pit mine estimation factors can be found from CostMine. Assuming that the largest mine in the world is also the most efficient, the cost of operating this mine was estimated. Next, the output of Hamersley, and its associated energy cost, were scaled to the amount required for the 2015 domestic car production of the United States. Based on the data from CostMine, it would cost a mine producing 5000 tons of ore a day 653 kWh per day to run, along with 4751 liters of diesel fuel per day. Scaling this value to production for a full year would account for roughly 1% of the production of Hamersley. This means it would require Hamersley some 475,100 liters of diesel per day and 65,300 kWh of electricity per day.

Steel production and cast iron production would require 11.81 and 1.345 million tons of iron ore respectively, for a total of 13.155 million tons of iron ore required. Using these same estimate from the Hamersley mine output, the cost of mining the ore is 7.3% of the total cost of running the mine for a year. Since the mine is estimated to be consuming 475,100 liters of diesel per day and 65,300 kWh of electricity per day, the auto industry would be responsible for 34,721 liters of diesel fuel, and 4772 kWh per day. Based on this estimate, the production of cars in the United States would require 2.8 million gallons of fuel and 41.8 million kilowatt-hrs per year.

Next, the amount of bauxite required for annual car production in the United States was considered. Currently, aluminum in general is composed of 33% virgin aluminum, and 67% recycled aluminum. Based on this ratio and the mass of aluminum in an average car, about 2.25 million tons of bauxite must be mined. It is also important to mention that the refining of aluminum from bauxite is a difficult process, as is explored later in this paper. Once again the largest mines for bauxite and production of aluminum is in Australia, which accounts for about 22 percent of the global bauxite mining. Thankfully the International Aluminum Institute has kept detailed records on the extraction of bauxite worldwide. They estimate that, per ton of ore extracted, it costs roughly 1.5 kilograms of fuel per tonne and 5 kilowatt-hours per tonne (AG, Intersturct). Scaling these values to meet the needs of the 2015 car production in the US reveals that roughly 3.375 million kg of fuel and 11.25 million kilowatt-hours are required per year. These values are represented in Figure 1 and Table 1 below.

Table 1: Energy Requirement for Extraction

Mine Estimate	Tons	Fuel per year (gallons)	Electric Energy (kWh)
Iron	13,155,00	2,800,004	1,802,720
Aluminum	2,250,000	858,480	11,250,000

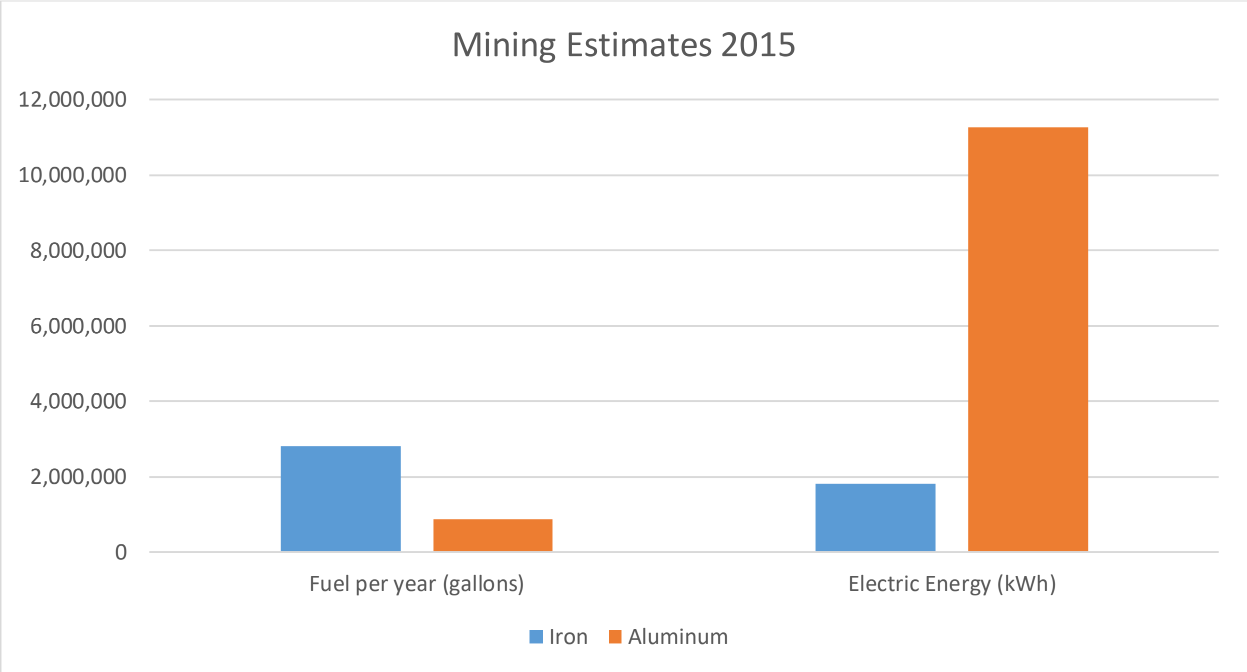

Figure 1: Estimated Cost of Mining

2.4 Refining

First, the refining of steel will be considered. Steel as was previously stated is broken into two categories, virgin steel and reclaimed steel. The average cost of power to produce reclaimed steel is 6 to 15MJ per kilogram (Norgate, Jahanshahi, and Rankin, 2007). Using a conversion factor of 1 pound to 0.45 kg will convert 6.3 billion pounds to 2.9 billion kg. This yields an estimate of energy to recycle steel ranging from a lower bound of 17.4 billion MJ to a higher bound of 43.5 billion MJ. The energy required to produce virgin metal is astronomical by comparison. The production of virgin steel, which also requires coal and limestone, takes 20 to 50 MJ per kg. Therefore, in order to produce the 18.9 billion pounds, or 8.6 billion kg, of virgin steel, 172 billion to 430 billion MJ is necessary.

On top of the already staggering amount of iron required for the steel is the iron ore required for cast iron production. At 6.4% of the car by weight, iron would be 224 pounds. Therefore, the production of 12 million cars will take 2.69 billion pounds, or 1.345 million tons of iron. The refining cost of the iron however is different from steel. One kilogram of cast iron costs approximately 20-25MJ of energy to be produced (Norgate, Jahanshahi, and Rankin, 2007). As a result, the production of 12 million car's worth of cast iron would consume 24-30 billion MJ in order to produce the necessary iron from ore.

Most aluminum in the United States is made from recycled aluminum. The smelting of aluminum is incredibly energy intensive due to the stable nature of aluminum oxide. Based on the previously stated assumption that a 3500-pound car will contain 8% aluminum by weight, a midsized car will contain 280 pounds of aluminum. Since 67% of the aluminum in a typical mix is recycled, an average car should have 187.6 pounds of recycled aluminum, with the remaining 92.4 pounds being virgin aluminum. When these numbers multiplied by the 12 million cars that were manufactured in the United States in 2015, the result is that 2.25 billion pounds reclaimed aluminum, and 1.11 billion pounds of virgin aluminum were required. The energy required to process reclaimed aluminum into an ingot is 219MJ per kg (Norgate, Jahanshahi, and Rankin, 2007). Converting to kilograms this equates to 1.01 billion kg and 221.9 billion MJ of power for reclaimed metal. In order to process bauxite into virgin aluminum, 227-342 MJ is required per kilogram, depending on how it is processed (Norgate, Jahanshahi, and Rankin, 2007). When these values are multiplied by their respective masses from cars produced domestically in 2015, the resulting energy requirements are 221.9 billion MJ and 113.4-153.8 billion MJ for recycled and virgin aluminum respectively.

Plastics, glasses, fabrics, and other polymeric materials make up the remainder of the vehicle by weight. Things such as the interior, dashboard, steering wheel, and seats are all considered non-metals in this paper. These plastics come in numerous chemical compositions and there can be dozens of different plastics in a vehicle. Because of this, and because the majority of the recycling done in scrap yards is for metal, plastics will not be considered in the energy cost of the vehicles. Fabrics also are not often recycled. Though seats in good condition can be resold, seats that cannot be resold also cannot be recycled through simple processes such as remelting. For this reason, and because of their minimal weight in the total vehicle, this paper will not include them in the energy cost of the vehicle.

The last remaining major component of the vehicles is rubber. Rubber is primarily found in the four tires that are on every car. The approximate energy cost to vulcanize tires from organic material is not readily available. However due to a trend of power plants burning used tires instead of coal the amount of released energy is available. Since 57% of the tire is organic in nature it releases 238 MJ per tire (Ferrer, 1997). Converting to kilowatt-hour and assuming a direct 1:1 energy transfer; that equates to 61.1 kWh in thermal energy released per tire. Assuming that this is at least the energy cost to fabricate the tires, then four tires per car at 12 million cars equates to 2.94 billion kilowatt-hours in energy. This is also based on the assumption that every car was produced with new tires. It also neglects to consider the energy cost of acquiring the materials for the process, and the factory cost in base energy to assemble the tires. This is only considering the amount of energy stored in the tire when they are synthesized. Due to this it can be considered that the cost of the tires is a low estimate.

Table 2: Energy Estimates for Refining Material

Material	Low Estimate (MJ)	High Estimate (MJ)
Steel (virgin)	172,000,000,000	450,000,000,000
Steel (reclaimed)	17,400,000	43,500,000,000
Aluminum (virgin)	113,400,000,000	153,800,000,000
Aluminum (reclaimed)	221,900,000,000	221,900,000,000
Iron	24,000,000,000	30,000,000,000
Tires	2,940,000,000	2,940,000,000

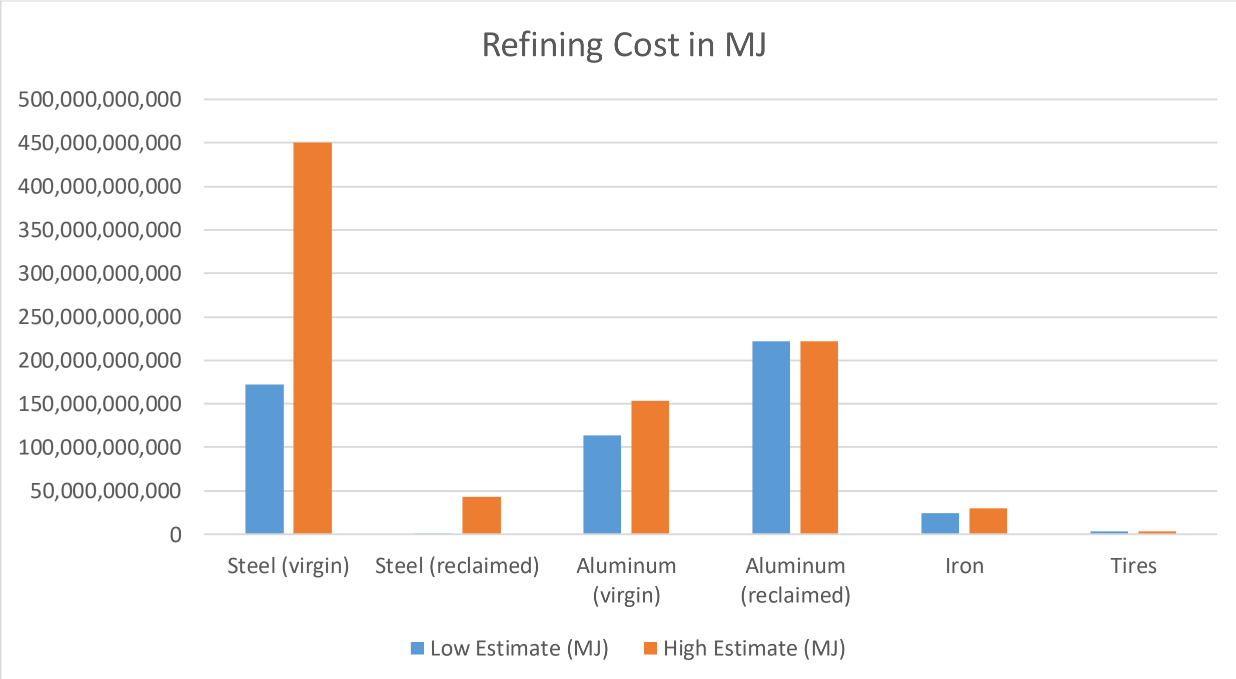

Figure 2: Estimated Cost for Refining

2.5 Production

The overall purpose of this paper is to define the amount of carbon footprint saved by the automotive recycling by the ARM. In order to calculate that, one must first determine the cost of mining, refining, and processing the material. The first two parts have been answered in terms of metals. To determine the manufacturing cost in terms of total energy one must first decide which facility is used to produce the vehicles. For the purpose of this study the following assumptions will be made. The first is that most plants are approximately the same size for major car companies, and the second is that the cost to operate them does not seriously change with location. Using the approximation by Business Energy Advisor, the average factory uses 95.1 kilowatt-hours per square foot per year. Accounting for the largest producer in America, the Ford Kansas City Assembly Plant which is some 4.7 million square feet produces approximately 460,000 vehicles a year. To account for the 12 million domestically manufactured cars in 2015, that means the factory would need to produce at 26 times production. In other words, it would require 26 of the largest factory in America to produce all the domestic vehicles of 2015. At 95.1 kWh per square foot, and some 4.7 million square feet that equates to 446.7 million kWh annually per factory. When this number is scaled by 26 to meet the 2015 domestic car production, the resulting energy cost is about 11.6 billion kWh of energy to manufacture the vehicles a year.

2.6 Carbon Estimate

Finally, the total carbon footprint of these processes will be considered. The energy which will be input to approximate the carbon footprint is a simple linear addition of the previously described components. This energy cost is then considered to account for the carbon footprint of the entire operation. It is important to note the exclusion of transportation from this estimation. This is due to the incredibly complicated and varied nature of the system. In more specific terms, it would be infeasible to chart where the material was extracted from and refined, and it would be impossible to account for the millions of dealerships and the cost to ship finished products to them. For those reasons the paper will consider the carbon cost without the cost of shipping. Shipping however would add millions of gallons of fuel for both truck, barge, and plane. The shipping cost though cannot be approximated without assuming a location of the mines, paths to the coast, and then where the factory is.

Carbon footprint became a matter of public concern in the 1990s and early 2000s. As the Cold War ended and the world was no longer focused on existential treats to its existence, Western governments and citizens began to focus on the way energy was produced. In the late 1990s it was becoming increasingly obvious that the polar ice caps were melting. This along with the ozone holes forming over Siberia was the beginning of the relevance of carbon footprints. Every product has a carbon footprint, which is the cost in carbon dioxide gas required to produce that item. Ironically some of the highest carbon footprints are in agriculture, the automotive industry as part of the industrial sector has a high impact as well. This paper will consider carbon footprint in two ways. One as the total cost of kilowatt-hour of the total energy, and two as the total amount of fossil fuel burned to produce that energy. The later will be give the reader the amount of cubic carbon feet that the automotive industry produces yearly by this papers estimations. It is worth noting that there is no full spectrum estimate available and these numbers have been estimated from a variety of sources and assumptions.

First to be considered is the mining cost. Bauxite ore, totaling a required 2.25 million tons of virgin material would require some 11.25 million kWh of energy and 3.375 million kg of fuel per year. This fuel cost converted to gallons per day to match the units of steel production is 858,480 gallons of fuel a year.

The cost of mining iron for steel and iron totaled 41.8 million kWh a year. The fuel cost totaled is 2.8 million gallons of fuel.

Next are the smelting and refining energy costs for all three of the ores. As previously stated the steel is 75% virgin and 25% recycled steel. For the purpose of this paper the supply of recycled steel comes without an environmental impact to “extract” in the same way that mining has a cost. The conversion cost in energy for the recycled steel is 17.4 billion MJ and as high as 43.5 MJ. The cost for virgin steel is 172 billion to 430 billion MJ. A conversion from megajouls to kilowatt-hours yields a cost of 4.8 billion kilowatt-hours to 12 billion kilowatts/hour per year. The virgin steel requires 47 billion kilowatt hours per year.

The cost of smelting and refining reclaimed aluminum is reclaimed 219MJ per kg; this equates to 1.01 billion kg and 221.9 billion MJ of power. This equates to 61.7 billion kilowatt-hours per year for recycled aluminum. To refine the aluminum from bauxite ore costs 335.3-375.7 billion MJ of power equating to 93.1 billion kilowatt-hours per year to 104.4 billion kilowatt-hours per year.

The required iron cost 20-25MJ per kilogram range, puts the energy at 24-30 billion MJ of power to produce the necessary iron from ore. Converting to kilowatt-hour it ranges 6.7 billion kilowatts/hour to 8.3 billion kilowatts/hour per year.

Now that the materials have been mined and refined that final step is to approximate the manufacturing cost of the 12 million vehicles.

This is done combining the energy cost of the factory calculation plus the calculation for the energy production for the tires. The calculated tally of the output of 26 Ford plants would require 11.6 billion kWh per year to produce the 12 million orders. The requirement for the production of tires is the 2.94 billion kWh per year of energy required to produce the 48 million necessary tires.

In summation of all these numbers it still bears mentioning that this does not count the theoretical transportation cost to move the raw materials and products from mines, to production facilities, to sales locations. The overall tally of carbon required can be viewed in the table below. Using the EPA site Greenhouse Gas Equivalencies Calculator, the team could calculate the 2015 carbon footprint. The team assessed that the entire carbon footprint of mining, refining, and producing the metal for a year of car production to be between 78,095,147 and 158,623,481 tons. The average or midpoint of this is 118,359,314 tons of carbon.

Table 3: Estimated Energy Requirement and Carbon Footprint for Producing Virgin Metals

Process	Energy Low Estimate (kWh)	Energy High Estimate (kWh)	Carbon Low Estimate (Tons)	Carbon High Estimate (Tons)
Mining	13,052,720	13,052,720	59,813	59,813
Refining	89,132,611,111	193.083,333,327	69,049,070	149,577,404
Production	11,600,000,000	11,600,000,000	8,986,264	8,986,264
Total	100,745,663,831	204,696,386,048	78,095,147	158,623,481

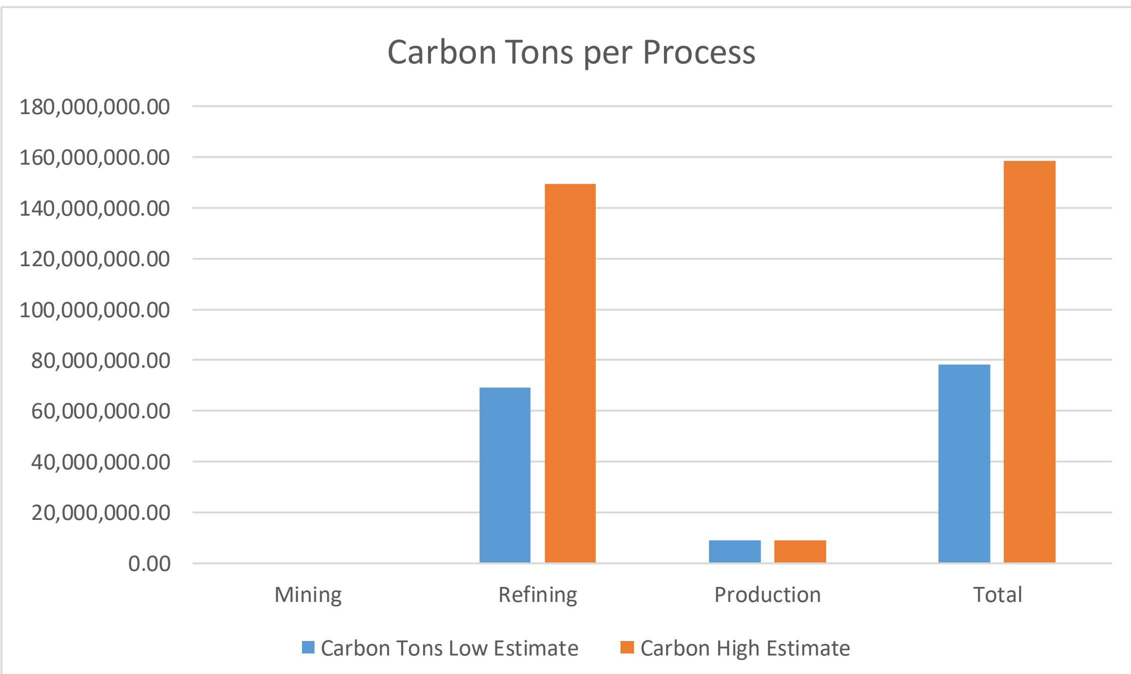

Figure 3: Estimated Carbon Footprint for producing Virgin Steel and Aluminum

2.7 Overview of Massachusetts Regulations for Hazardous Materials

The first part is to state the rules and regulations. According to the state of Massachusetts Department of Environmental Protection (DEP) website, the current regulations for 2017 are paraphrased below.

Used Motor Oil: Used motor oil must always to be recycled and never thrown away. Motor oil should never be poured into a watershed, the ground, or any public sewage system. Oils contain heavy metals harmful to flora, fauna, and humans. A single gallon of oil can pollute as much as one million gallons of drinking water. A pint of oil can create a slick contaminating an area the size of a football field. For proper disposal of oil, the majority of municipalities offer a collection service. Many local landfills or refuse disposal services will accept used oil. If this option is unavailable used motor oil can be brought back to the original place of sale. By law anyone selling oil is required to accept up to two gallons of oil a day from a single customer, given proper proof of purchase from the original transition. Some businesses such as gas stations will accept the oil without receipt as well. Motor oil, when mixed with other fluids, can be burned to generate heat and or electricity (DEP, 2013).

Used Oil Filters: Oil filters can be disposed of via the trash, as long as the oil is drained and gathered from the filters, the dry filter can then be discarded with normal waste products. The drained oil should be added to the other drained oils from the vehicle. This oil is either disposed of or in the case of most ARM members burned for heating (DEP, 2013).

Antifreeze: Antifreeze is generally regarded as one of the more harmful chemicals in a vehicle. This is due to its sweet taste and odor. Antifreeze is especially harmful to both children and wildlife that are not aware that antifreeze is a poisonous chemical. Recommendations by the Massachusetts DEP can be found at their website. In summation, they recommended saving waste fluids in childproof containers and checking the local municipality website for collection times and dates (DEP, 2013).

Dead Batteries: The state requires that batteries be properly disposed of at a collection center and not thrown away in the trash. These sites can be found at the local municipality websites or at the aforementioned Massachusetts DEP site.

3. Methodology

The objectives set forth by the ARM sponsor were the following:

1. Determine the number of vehicles recycled in Massachusetts annually
2. Quantify the volume and diversity of automotive parts that are reclaimed from salvaged vehicles
3. Determine the environmental benefits of properly recycling hazardous materials
4. Determine the environmental impact of recycling automotive parts with respect to the product of new parts from virgin materials

Our team used a varied approach that allowed us to acquire information from a diverse set of methods. Overall, we had three steps:

1. Analyze the current literature and previous work that had been done to establish a reference point of understanding
2. Conduct site visits to identify current practices with regards to automotive recycling in Massachusetts
3. Collect and analyze data from the members of the ARM

3.1 Analyze the current literature and previous work that had been done to establish a reference point of understanding

In order to determine the environmental effects of the automotive recycling industry, the overall system of producing cars must be known first. In order to do this, the production of cars in general was analyzed in terms of energy required and environmental effects, which is represented by the carbon footprint. This analysis involved extensive research of the current automotive industry and an approximation of the energy required by the industry, and the environmental impact that the utilization of this energy produced. Due to the size, complexity, and the proprietary nature of this industry, several assumptions and simplifications had to be used in order to arrive at a conclusion given the available resources. These assumptions are stated within the analysis.

3.2 Conduct site visits to identify current practices with regards to automotive recycling in Massachusetts

To gain an understanding of the kind of practices that are currently in use in regards to car recycling, we will conduct detailed site assessments in various Massachusetts auto-recycling facilities. The site assessments will include tours of the facilities and interviews with employees. This will allow the team to obtain a clear image of all the different methods used by the facilities in order to take care of each part of a vehicle.

3.3 Collect and Analyze Data from ARM Members

Survey

After a generalized understanding of the operation of the automotive recycling facilities was established through site visits, a survey was composed for the purpose of gathering the necessary information from as many automotive recyclers in Massachusetts as possible. More specifically, the survey had three main objectives. The first was to determine the size of the facility. The other two objectives were to determine the mass flow and energy flow into and out of the facilities. This survey was important as it provided us with input from the members of the ARM. A complete version of the survey questionnaire is provided in Appendix A. The questionnaire was built so that the members would provide us for a period of one month, i.e. how many cars do you take in one month on average? How much electricity is used at your facility in one month?

In terms of structure, the survey was composed of open answer responses to questions which typically asked for a numeric value. This structure of answer would enable the recyclers to record as accurate a response as possible, without being limited by the constraints of choosing from a multiple choice. These questions also provided a choice of units or selected a specific unit in order to simplify data analysis and reduce errors from conversions. The units were selected based on the most probable unit that the business would work with, such as kilowatt-hours for electricity and gallons for heating oil. This was done in order to streamline the process of completing the survey for the recyclers, and to reduce the chance of errors from converting between units. While some questions provided several choices for which units to report the answer in, this was not used unilaterally due in part to limitations of the software through which the survey was conducted. In situations where one of several unit systems could be used, one of two answering options were implemented. The first was to provide a few choices of unit, and the second was to enable the business representative to input whichever units were most convenient.

Analysis of results

There are 60 members of the organization and nine associate members. The response rate was 13%— a total of nine responses were received. A detailed analysis of the survey response is discussed in the results section. From our survey we understood that there was a large range of facilities in Massachusetts, with the majority of them being on the small scale, family run business. The project team then extrapolated the results to scale them for values for a year statewide.

We analyzed the results of the survey by compiling the numbers collected from the ARM members. One of the questions was to know the top ten most selling parts of each recycling facility. We gathered the most common parts throughout Massachusetts and found the ones that are most common. From the ones that were most common, we calculated the environmental impact of the recycling operations. The calculation of this was done by using Sustainable Minds- a software.

Using Sustainable Minds

After completing data collection, next step was to determine the impact of environmental recycling automotive parts with respect to the production of new part from virgin materials. To achieve that, the team used the "Sustainable Minds" software. We provided the software with the materials, the amount of the materials, and the procedures these materials undergo to become parts. The software then provided the team with estimates on the carbon footprint of the whole production procedure of the new parts.

Furthermore, the team now had to compare this results to the carbon footprint of the ARM to that of the new parts production. For the ARM's carbon footprint, we removed the cost of scrap metal from the cost of new materials and subtract the kWh of the ARM operations.

4. Results

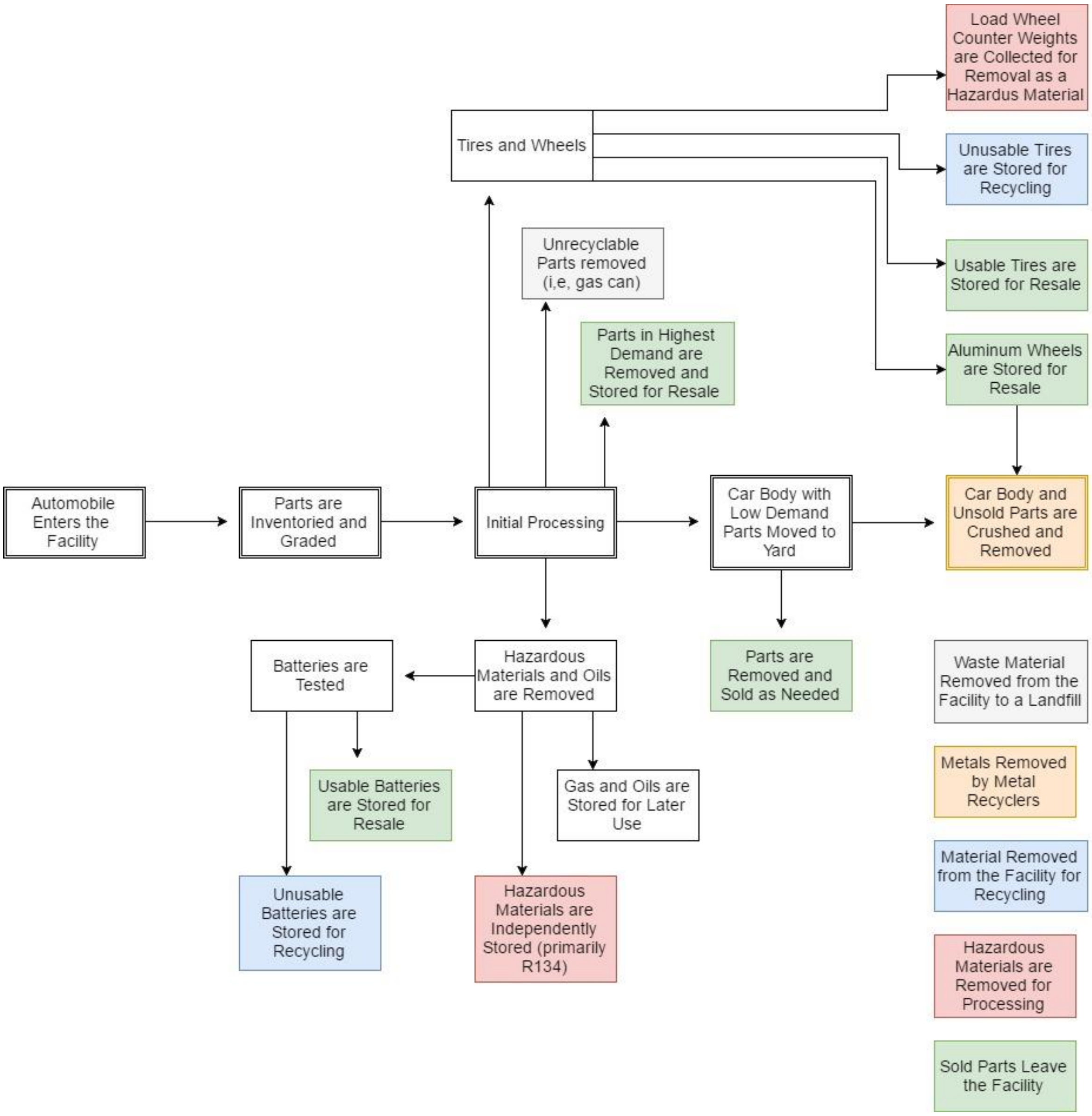

Figure 4: Qualitative Mass Flow within a Recycling Facility

There were a few ways the dismantling facilities took in the cars. The most common method was through online auctioning. Larger dismantling facilities such as Linder's Inc. and Roberston's Auto Salvage usually had a list of items required, based on most popular products and the need of items in the marketplace. Other methods of acquiring vehicles included individual sellers, and cars that are brought in by towing companies. The process for selecting a particular vehicle was based on how many parts of the car were salvageable, condition of the vehicle and price.

Once a salvaged car enters a recycling facility, it may be processed differently depending on the facility. However, the processing of the salvaged vehicle will follow a general outline regardless of the facility in which it is processed. This outline is summarized visually in Figure 4.

When a new salvage car enters a facility, it is given a thorough examination and undergoes some basic tests to determine the quality of the parts in the vehicle. The external parts are examined visually and graded, and internal components such as the engine are briefly tested to determine if it will operate properly. Each part and its grade are recorded in an online system.

The parts that are required for inventory are stocked. A representative image of an inventory stock from the Atlantic Salvage Facility is shown in Figure 5. This inventory is reflective of the larger facilities

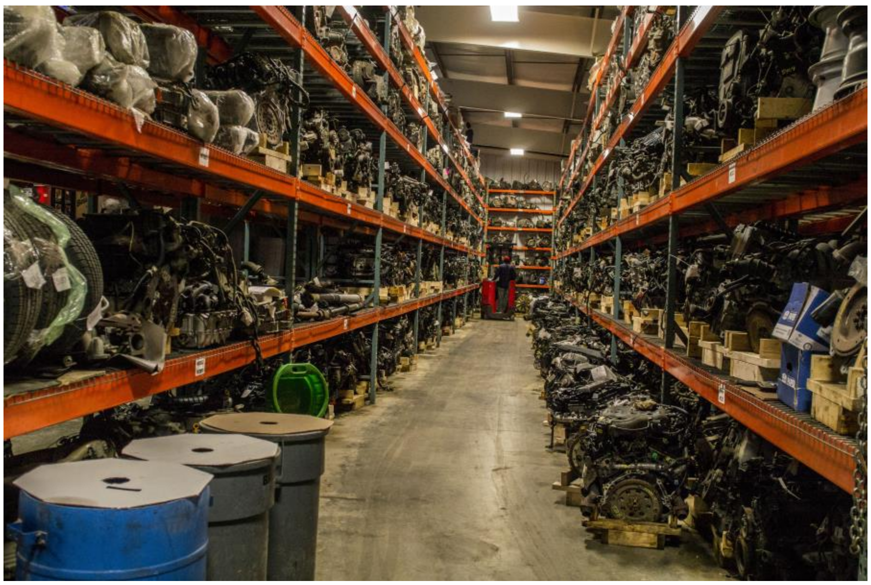

Figure 5: Inventory at Atlantic Salvage
(Atlantic Used Trucks & Salvage Corp., Lowell, MA. Atlantic Salvage. Web. 19 Apr. 2017)

Once the external parts are examined and inventoried, the vehicle is brought to an on-site mechanic shop of its initial processing. Most of the work that will be done with a salvaged car will be done in this stage. In this stage, parts that cannot be used, such as the gas can, are removed. Additionally, all fluids are independently drained from the car, and stored appropriately. Figure 6 is an image from Henry's Auto Parts displaying a regular dismantling space.

The battery is removed and tested. If the battery is operational, it can be stored for sale, and if it is not, then it is stored for delivery to a battery recycler. Parts that are in sufficiently high demand will be removed and stored separately for sale. Other parts may be released from internal restraints to facilitate removal later if needed. Components that are not usable, but lightly damaged, which are known as cores, will be removed and stored to send to a remanufacturer. The wheels will also be removed. This enables the easy removal and storage of the lead counterweights from the wheels, which are environmentally hazardous. The tires will be removed as well and stored for either resale or scrapping, depending on the condition of the tire. The remaining alloy wheels are stored separately in order to keep the aluminum alloy separate from the mixed alloys in the rest of the car. The catalytic converter is removed and stored separately as well due to its platinum content. Once this processing is done, the car is moved to the yard for storage with its remaining, low-demand parts. Figure 7 is an image displaying yard space where vehicles and low demand parts are kept.

Figure 6: Preparing a Car for Dismantling at Henry's Auto Parts
("Henry's Auto Parts, LLC." Henry's Auto Parts, LLC,
www.henrysautoparts.com/ReDirect.htm?xferto=DispImg&imgname=..%2Fphotos%2Fdismantling4.jpg&color=INDIANRED&indi=0&indj=4. Accessed 25 Apr. 2017)

Figure 7: Robertson's Auto Salvage Yard
(Robertson's Auto Salvage, Wareham, MA. Robertson's Auto Salvage. Web. 19 Apr. 2017.)

After the car has been moved for storage in the yard, parts will be removed as necessary. The car may be moved to the shop again if necessary to remove a large or cumbersome component. In this stage, the car and its parts remain relatively inert due to the shielding of the components from the elements by the body of the car. Additionally, the salvaged car will not react negatively with the environment during this time because the hazardous materials and parts are no longer present.

Once It has been decided that the space in the yard is more valuable than the car body and its remaining parts, the salvaged vehicle will be prepared for crushing. Depending on the business practices of the particular facility, this may involve the removal of parts made of aluminum, copper, or other non-ferrous metals or alloys, or simply moving the car to the crushing site in the yard. The car will then be crushed and sold to metal shredders and recyclers, in addition to the other non-ferrous scrap metal.

At this point, the entire mass of the salvaged car should have left the facility in some way. Parts in high demand will be sold to customers. Cores will be sent to remanufacturing facilities. Hazardous material will be removed for proper processing and disposal by a third party. Oils and gasoline will be used for heat or to power other machines. Scrap metal will be removed for recycling. Finally, refuse will be sent to a landfill.

Variation Within the Results

During the processing of data, the team noted wide discrepancies in the data received from surveyed members of the association. The data varied largely based on the number of cars processed in a month, ranging from 19 to 960 cars a month. The team also surveyed for number of employees and for acreage. This did not yield any correlation as shown in figure below. This disconnect is best shown in the cases of lots that share the same number of cars or employees but a wide difference in the other. For example, one lot had 85 employees and processed 425 cars a month; another facility had 85 employees but processed 960 cars a month. Another example is that three lots that each had five employees. Their number of cars processed per month were 19, 50 and 65. This wide discrepancy is due primarily to the business structure of each operation. An operation that chooses to focus on a smaller number of cars is more likely to hold cars longer and strip them of parts for sale. Larger operations that have access to larger volumes of cars are more likely to process cars quickly and sell more of the car as scrap metal in the crush. This variance is also illustrated in the weight of a crush. Based on the information given by two respondents the weight of a crush was estimated to be 1900 pounds and 2600 pounds. These two yards differed largely in size of operation in both employee and cars per month. This highlights the difference in the business model. The lower weight average crush was from a smaller yard that presumably sold more parts off each vehicle before converting the remainder to a crush. The larger estimate was from a higher volume operation that processed more vehicles and was presumably more focused on total volume and turnover of their inventory, hence the higher crush weight.

Taking this into consideration that the yard’s responses vary heavily by location, market, and business philosophy the team opted to take the data as an accurate subsection of the ARM as a whole. Since no correlations could be drawn based on acreage, volume, or personal the team decided the most accurate representation of the data was to simple average the responses of the members. The team has included spreadsheets of formulas and estimates of carbon per ton, per car, and per lot. This is done for the ARM that if they acquire more responses in the future can adjust the conclusions of this paper to further reflect a larger sample size of the ARM.

4.1 Determine the Number of Vehicles Recycled in Massachusetts Annually

The range of cars processed in a facility in a month was obtained by taking the range of the responses from the survey sent to the ARM. This range is from 18 to 960 cars processed in a month in a facility based on the size of the facility.

To approximate the number of cars processed by ARM members in a month, the survey results were extrapolated to the rest of the ARM members. This extrapolation was based on the assumption that the survey results were representative of the whole of the ARM. Therefore, the sum of the results from the survey was scaled to the total number of ARM members from the number of survey responses received. The result of this extrapolation was 165500 cars per year.

4.2 Quantify the Volume and Diversity of Automotive Parts that are Reclaimed from Salvaged Vehicles

The variety of parts that theoretically can be recovered from a vehicle essentially encompasses the entirety of the car. A list of 157 possible parts that can be salvaged can be found in Appendix B, where they are grouped by type for grading.

The number of parts that can be and are recovered practically is a much smaller number which depends on a variety of factors, including market demand for the part and the condition of the part in the salvaged vehicle. Since parts are removed from the vehicles for sale, the amount of parts that are recovered is the number of parts sold. Based on this, the range of the most common parts that are recovered can be found in Table 4 below.

Table 4: Range of Sales of Several Parts by ARM Members Per Month

	Wheel	Doors	Engines	Transmission	Tail Lights	Mirror
Minimum	30	8	5	8	35	22
Maximum	414	1100	450	425	300	281

4.3 Determine the Environmental Benefits of Properly Recycling Hazardous Materials

The state of Massachusetts laws out various guidelines for the proper disposal of various oils and chemicals. These include chemicals such as mercury, windshield wiper fluid, and oils such as gasoline, engine oil, and transmission oil. In order to assess the various scrap yard represented by the ARM the team used the following criteria.

1. Were the sites aware of the requirements?
2. Were the visited sites compliant with these requirements?
3. Are the unvisited sites be complying with regulations; assessed via the survey.
4. What are the environmental effects of improper disposal?

After reviewing all of the requirements for proper disposal the team began evaluating the removal procedures of scrap yards while on site visits. The team found that of the four sites visited all four of them complied with the regulations. Through observations and questions the team also found that the majority of oils are saved for burning. The team did not inquire into the mixing percentages of oils but observed no reason for alarm with the system of saving oils for onsite usage. The most common usage of the oil was for heating the facilities, to be burned throughout the winter in appropriately sized and rated large oil furnaces. Some facilities were keeping the oil containers in separate sheds from their work environments, these facilities said it was by request of the local fire department. If the team was to make any recommendation on oil it would simply be to check with local fire department about proper storage techniques.

Regarding gasoline, the team observed similar findings. The facilities all saved gasoline for personal usage in their automobiles or work vehicles. Once again the team found nothing wrong with this practice and were generally impressed with the frugal move. If anything saving gasoline for use rather than disposal should be encouraged if any ARM members are not doing so already.

Regarding harmful chemicals that were not oils the team found no issue with disposal techniques. The team found that all wiper fluids, antifreeze, refrigerants and other chemicals were being collected and properly disposed of. Once again the team observed some operations that would save certain chemicals for personal usage if they felt the need. Another common theme was the local partnership with other business to either sell or give away chemicals. This included Freon's and refrigerants that were sold by one scrap yard to a local business dealing in air conditioners and refrigeration systems. Ultimately all chemicals were disposed of and all owners at the site visits were able to quickly explain how the chemicals are removed, collected, and disposed of. The only team recommendation would be to increase local partnerships if possible, if another business will buy any of these chemicals it should be encouraged ARM members seek them out for transactions.

Batteries were separated into two obvious categories: dead batteries and serviceable batteries. Serviceable batteries were tested and resold when possible. As for dead batteries, these were separated from the vehicles and collected for scrapping. Since scrap batteries can be resold they were collected and sold by the yards. In terms of this project that qualifies as the proper disposal of the batteries since they were properly handled by the yards and removed appropriately. All batteries are collected from vehicles and processed either for resale as useable batteries or sold in bulk as cores, and no yards were throwing away batteries or putting them into cars to be crushed.

The last major category of being tires will be addressed at length in other portions of the paper. To summarize for this section though all tires were removed and sorted into the categories of resale or recycle. The tires for resale were obviously resold and left the yards in that manner. The recycle category of tires were often saved and stored until the yard had made arrangements for removal. The tires were all appropriately scrapped and or resold as used tires. None of the sites were found to be throwing the tires away or disposing of them in any other less optimal manner.

The ranges and averages of the above mentioned materials can be found in Table 1Table 5. As stated previously these responses will vary heavily based on the volume of cars that each operation handles. Ultimately the important thing to note is that each site disposes of their material properly and efficiently.

Table 5: Range of Hazardous Materials Collected by ARM Members

Hazardous Material	Amount per Year	
	Low Estimate	High Estimate
Batteries	400	8,600
Gasoline	750 gallons	41,000
Assorted Oils	3,600 gallons	38,000 gallons
Refrigerants	70 gallons	220 gallons

In regards to the project, the team determined the burning of gasolines and oils is negligible. The overall energy cost of each operation was collected in the forms of the energy bills. The final energy bill should include the cost of oils and gasses burned for heating. Due to this the overall energy cost of each operation simply considers the reported kWh per month.

4.4 Determine the Environmental Impact of Recycling Automotive Parts with Respect to the Production of New Parts

In regards to the environmental impact the team followed a simple method for accounting for the ARM members. First they averaged the responses to get an average yearly value for cars processed in an average facility, which was 2605. Second, these values were compared to those calculated in the literature review. Using the background data and dividing by the original number of vehicles and then by the weight of a ton for the carbon equivalent per ton of metal. The following table represents the tons of carbon produced as byproduct when producing a ton of metal. The virgin category is from ore. The reclaimed is from scrap metals. The third column is the net reduction in carbon tons if reclaimed metals replaced virgin metals.

Table 6: Carbon Footprint of Producing Metals

Metal	Virgin	Reclaimed	Reduction in Energy
Steel	7.1	1.5	5.6
Aluminum	51.8	8.1	43.7

Subtracting the cost of reclaimed minus the virgin gives the net gain in carbon per ton. This is logic is justified in the sense that each ton of metal scrapped by an ARM member equates to 1 ton that is not required to be produced virgin from ore. This multiplied by the 2605 average yearly volume of cars equates to roughly 31,200 tons of carbon a year per yard.

This times the 60 members of the ARM and the other 9 non ARM members equates to 2.2 million tons of carbon in yearly reduction a year. This breaks to roughly 11.9 tons of carbon saved per car scrapped. One of the largest assumptions taken with this method is assuming that the entire car is scrapped. Even if a part, such as a door, is sold separately, the metal from that door is effectively recycled because the sale of it as a parts eliminates the necessity for a new door. Eventually that door will make its way back through the system when the car it is on is recycled. In this sense the team considered that everything that enters the yard eventually leaves the yard. Please see the appendix section for the spreadsheets for these calculations. All spreadsheets and formulas are provided to the ARM as a convenience that if they acquire more data points these estimates can be adjusted.

Life Cycle Analysis

Once several of the most commonly recovered parts were identified, an assessment of the carbon footprint of the production of these parts was completed using Sustainable Minds software. This software could determine the environmental impact of the production of these parts, but only with information about how the parts were produced. Generally, the method of how each distinct component of the part was made and the material of the component was required. For example, a transmission has many linked gears connected with rods inside of a housing. The gears and housing can be made of different materials and through different methods. However, the specific production method and composition of critical components is not available due to its proprietary nature. As a result, the analysis can only be completed in a general sense. The following will list the assumptions that were used in obtaining the input values that were used in the LCA of the selected parts.

Transmission:

The overall composition of the transmission that was analyzed was retrieved from (Sullivan, Kelly, and Elgowainy, 2015). A 2011 Honda Accord transmission was used due to the frequency of the car and the availability of the information.

The bill of materials for the transmission included two principle materials, 29.8 kilograms of aluminum and 62.5 kilograms of low alloy steel. Using the Sustainable Minds program, it was decided that steel parts were formed by milling. Aluminum parts were formed by lost foam casting (Kalpakjian and Schmid, 2014).

Below is a graphical representation of the carbon footprint of manufacturing a transmission according to our breakdown of materials. Figure 8 represent the total quantity of global warming gasses created throughout the life cycle. The impact units are in kilograms of carbon dioxide equivalent since it accounts for all the gasses that continue to contribute to global warming.

Engine:

The overall composition of the engine that was analyzed was retrieved from (Sullivan, Kelly, and Elgowainy, 2015). A 2011 Honda Accord engine was used due to the frequency of the car and the availability of the information.

It was assumed that the engine block is made of 64.8 kg of aluminum alloy formed through high precision sand casting, which then underwent a heat treatment. It was assumed to have 85.6 kg of low alloy steel which was formed through milling and heat treated. Finally, it was assumed to have 15.1 kg of copper wire formed by drawing (Kalpakjian and Schmid, 2014).

Below is a graphical representation of the carbon footprint of manufacturing an engine according to our breakdown of materials and processes. Figure 9 represents the total quantity of global warming gasses created throughout the life cycle. The impact units are in kilograms of carbon dioxide equivalent since it accounts for all the gasses that continue to contribute to global warming.

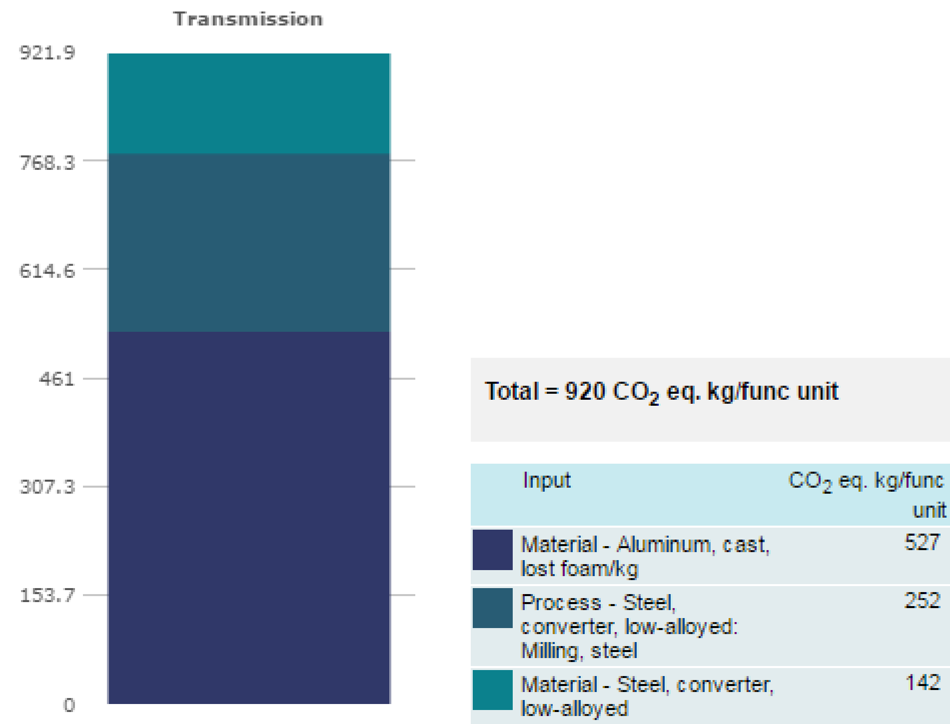

Figure 8: Environmental Impact of Producing a Transmission (2011 Honda Accord)

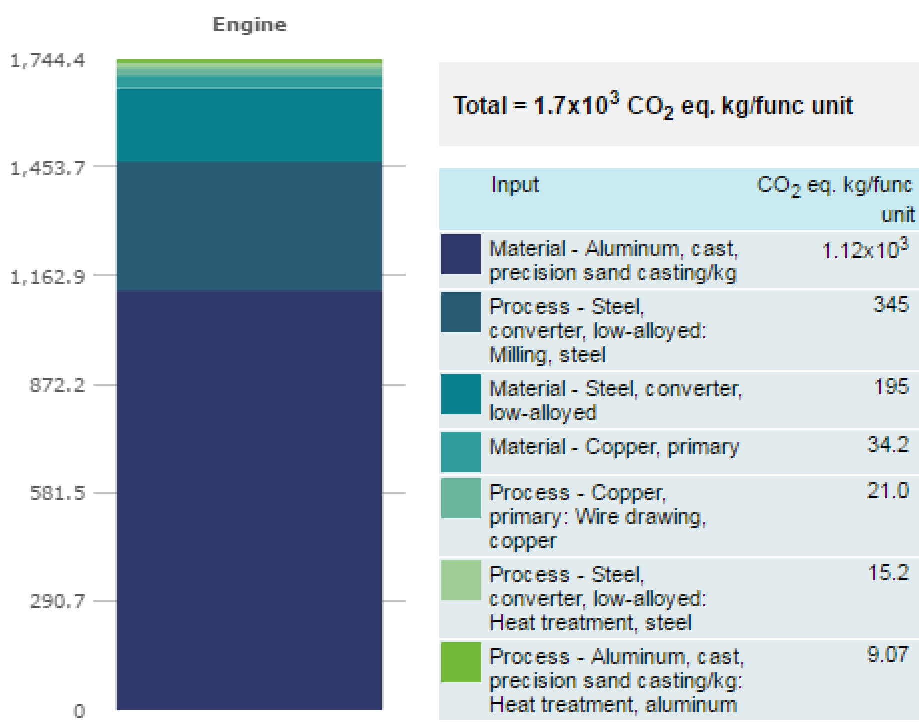

Figure 9: Environmental Impact of Producing an Engine (2011 Honda Accord)

Wheel:

The wheels were assumed to be made of 7 kg of aluminum alloy and given shape through casting using a semi-permanent, reusable mold. It was also assumed to have undergone a heat treatment (Kalpakjian and Schmid, 2014).

Below is a graphical representation of the carbon footprint of manufacturing a wheel according to our breakdown of materials and processes. Figure 10 represents the total quantity of global warming gasses created throughout the life cycle. The impact units are in kilograms of carbon dioxide equivalent since it accounts for all the gasses that continue to contribute to global warming.

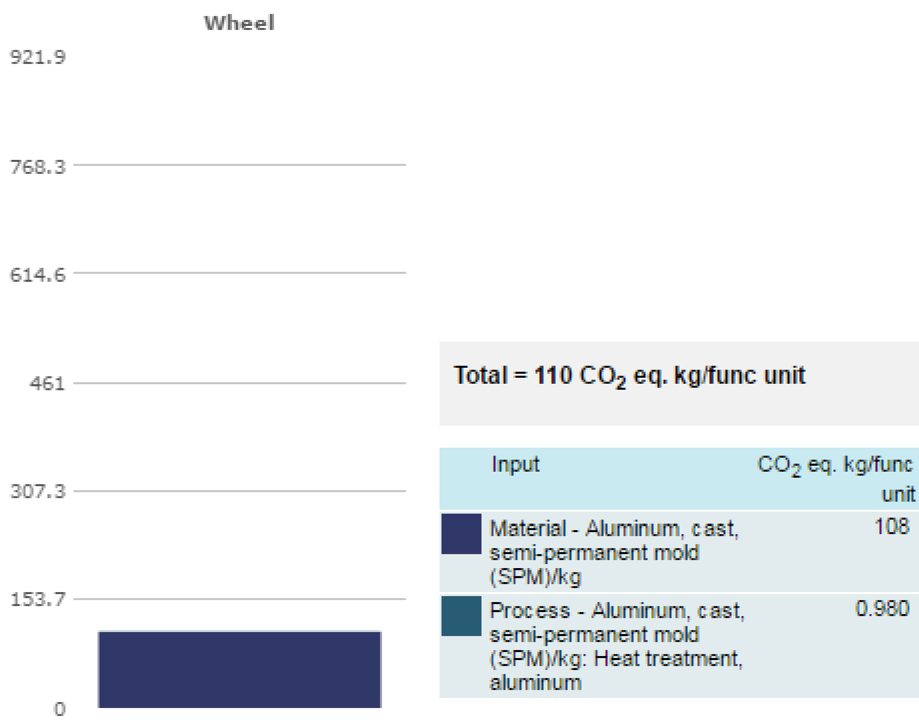

Figure 10: Environmental Impact of Producing an Aluminum Wheel

Tire:

The average weight of a new tire is 25 pounds and the average weight for a scrap tire is 20 pounds. It was found that a typical tire requires the following materials (Mark, Erman and Eirich, 1994, and Alliger and Sjothum, 1963):

- Synthetic Rubber
- Natural Rubber
- Sulfur and sulfur compounds
- Silica
- Phenolic resin
- Oil: aromatic, naphthenic, paraffinic
- Fabric: Polyester, Nylon, etc.
- Petroleum waxes
- Pigments: zinc oxide, titanium dioxide, etc
- Carbon black
- Fatty acids
- Inert materials
- Steel wire

The bill of materials that was input into the Sustainable Minds software was created based off of this information. However, this list of materials was fully incorporated into the software due to the resources available to the software. The final bill of materials can be found below in Table 7. The relative amounts of each material in a tire was obtained from Mark, Erman and Eirich, and Alliger and Sjothum.

Table 7: Typical Tire Compositions by Weight

Material	Percent Composition by Weight	Weight (lbs)
Natural Rubber	14%	3.5
Synthetic Rubber	27%	6.75
Carbon black	28%	7
Steel	14-15%	3.75
Fabric, fillers, accelerators, antiozonants, etc.	16-17%	2.125

Below is a graphical representation of the carbon footprint of manufacturing a tire according to the previously stated breakdown of material. Figure 11 represents the total quantity of global warming gasses created throughout the life cycle. The impact units are in kilograms of carbon dioxide equivalent since it accounts for all the gasses that continue to contribute to global warming.

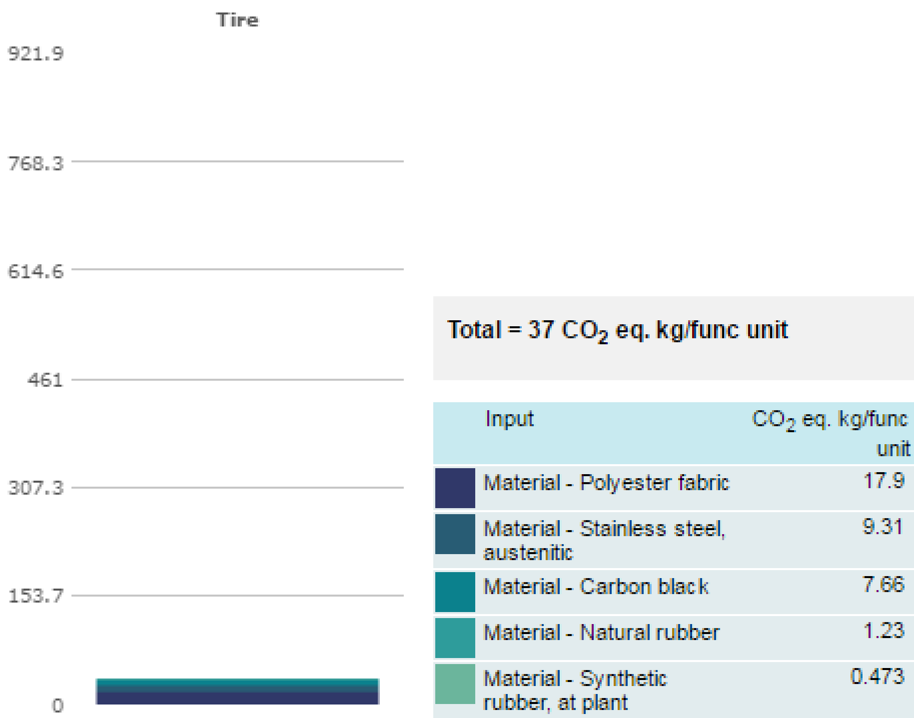

Figure 11: Environmental Impact of Producing a Tire

5. Conclusion

The goal of this project was to assess the environmental impact of the Automotive Recyclers of Massachusetts, meaning to understand the impact the ARM has on the state's carbon footprint. The team worked to accomplish four objectives that had to be answered to achieve this goal. After research, data collection, and extensive analysis of both sets of data, the objectives were answered, and thus the impact was defined.

From the surveys taken from the ARM members, the first objective was extrapolated. That would be the number of cars annually processed by the ARM, which is 165,500 cars. For the second objective, to quantify the volume and diversity of the automotive part reclaimed and salvaged, similar extrapolation method with objective one were used and the most recycled parts were identified. The third objective concerned the hazardous material involved in the automotive recycling process, such as battery fluids, gasoline, refrigerant, etc. Estimates of the amounts collected annually were made from the data. All facilities were in compliance with the state regulations and almost all the fluid were reused in house. For the last and fourth objective, the team had to determine the actual impact that the industry has on the environment. To accomplish that, the team decided to compare the reuse of specific parts with respect to the production of new parts from virgin materials. As a result, the ARM was assessed to reduce the carbon emission of the state by 38,200 tons of carbon per lot in Massachusetts.

Scope Limitations and Future Work

In the beginning of the study, the team realized that a complete analysis of this entire recycling business could not be able to be completed in a single project. Accordingly, the team narrowed the focus of the project and set parameters that made our research manageable. The focused area of study for the project was dismantler operations in Massachusetts. Effectively this meant that we would concentrate on the facilities only. The approach utilized by the team consisted of understanding how much material was going inside these facilities. Therefore, the analysis that was completed did not include the individual operations of the other facilities that process related materials. Additionally, the team did not consider the amounts of materials that are generally unrecyclable, especially on the scale that would be required for this industry.

Future work in this area would be most beneficial if it were to address the areas that were not considered in this assessment. The easiest next step would be to consider the metal recyclers that receive and recycle the metals from the dismantling facilities. This could also include the much more difficult analysis of the automotive residue, which is a collective term for the non-metallic materials that are remaining in a crushed car.

6. Recommendations

Based on the data that was collected and the subsequent analysis if that data, the team would recommend that the ARM use these results to increase the community awareness to the environmental benefits that the automotive recycling facilities offer.

The team would suggest that another small project to test the used parts against new part could be beneficial. This sort of project could define the potential performance differences between new and reclaimed parts. If the reclaimed parts perform comparably to new parts, as would be possible with steel components operating under loads below the fatigue limit, then a major factor that could influence buyers could be defined.

Additionally, if the ARM would want to had a complete understanding of the entire recycling process, then the team would suggest that other projects could be conducted in order to obtain a full understanding of following steps in the recycling process, including the specific processing of the scrap metals and hazardous materials that leave the facility.

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Appendix A: Survey

The questionnaire sent out to the members of the ARM

1. Basic Information
2. How many cars does your facility received in an average month
3. How many people does your company employ?
4. How many acres is your yard?
5. What are the top 10 most popular parts you sell? Please list them and estimate units sold in a month
6. How many cores do you sell a month, in terms of weight? If you don't know the weight, please write the number of pieces or parts sold in a month
7. On our site visits, we saw that materials deemed hazardous by government regulations such as antifreeze or mercury switches were collected separately, then picked up from the facility by a third party for processing. Does you facility follow this same protocol? If not, please elaborate on how hazardous waste is processed or managed. Please indicate 'Yes' if you facility follows the same protocol, if not, please explain
8. How much refrigerant/coolant do you collect at your facility in a month?
9. How much refuse is sent to a landfill in a month, in terms of weight?
10. How much material do you sell or send off to crushers and/or shredders in terms of weight? Please specify units per unit time
11. Please estimate how much scrap is sent off site. Specify units per time. Please include the following categories: Unsorted (mixture of steel and aluminum, excluding catalytic converters), Steel, Aluminum, Catalytic Converters, Tires, Batteries, Crushed Vehicles, Other
12. What materials, if any, are used in-house, such as leftover engine oil or gasoline? Please estimate how many gallons are recovered and used n a year if applicable. Please list all types of materials, such as: Gasoline, Motor Oil, and if there are others, please name them
13. How much purchased oil is burned at your facility in a year, in gallons? Please do not include reclaimed oils
14. How much electricity is used at your facility in a typical month in Kilowatt-hours (kWh)?
15. Does your facility directly utilize any renewable energy sources? If so, please list what kind
16. If your facility directly utilizes renewable energy sources, please estimate how much energy is produced in a month in Kilowatt-hours (kWh)

Appendix B: List of Parts

The following parts types will be considered Body Parts (Graded on units of damage)			
100	Front End Assembly	197	Fuel Tank
101	Front Bumper Cover	154	Pickup Truck Cab (Shell)
102	Header Panel Assembly	155	Pickup Box Rear
103	Spoiler/ Valance, Front	159	Quarter Repair Panel
104	Grille	160	Quarter Panel Assembly
105	Bumper Assembly, Front	164	Cab Clip
109	Radiator Core Support	169	Spoiler, Rear
110	Fender	170	Decklid / Tailgate
117	Hood	190	Bumper Assembly, Rear
120	Door Assembly, Front	194	Tail Panel
130	Door Assembly, Rear or Back	195	Tail Finish Panel
140	Back Door	198	Center Pillar
150	Rear Clip	311	Oil Pan
152	Roof Assembly	108	Bumper Shock

The following parts types will be considered Mechanical Parts (Graded based on Miles)			
118	Hood Hinge	476	Beam Axle, Loaded
125	Door Window Regulator, Front	490	Stub Axle, Rear
135	Door Window Regulator, Rear	505	Upper Control Arm, Rear
163	Tail Gate Window Regulator	510	Knee
185	Rear Window Washer Motor	511	Upper Control Arm, Front
188	Rear Window Washer Motor	238	Steering Column
512	Lower Control Arm, Front	257	Speedometer Head/Cluster 515 Spindle/ Knuckle, Front
513	Lower Control Arm, Rear	516	Leaf Spring, Front

300	Engine Assembly	517	Coil Spring
302	Cylinder Block	518	Leaf Spring, Rear
303	Crankshaft	520	Front Axle I-Beam
305	Camshaft	521	Torsion Bar
306	Cylinder Head	524	Stabilizer Bar
309	Harmonic Balancer	527	Strut
320	Carburetor	530	Brakes, Front
321	Turbocharger/ Supercharger	533	Brakes, Rear
322	Fuel Injection Parts	536	Caliper
323	Fuel Pump Assembly	538	Hub
324	Water Pump	540	Power Brake Booster
326	Fan Clutch	541	Brake Master Cylinder
337	Throttle Body/ Valve Assembly	545	Anti Lock Brake Parts
341	Air Injection Pump	551	Steering Gear/ Rack & Pinion
349	Camshaft Housing	553	Power Steering Pump
370	Fuel Injection Pump	600	Battery (Hybrid or Electric Vehicle)
372	Vacuum Pump	601	Alternator
400	Transmission/ Transaxle Assembly	604	Starter Motor
401	Overdrive Unit	606	Distributor
406	Pressure Plate	615	Blower Motor
407	Torque Converter	617	Power Window Motor
409	Flywheel/Flex Plate	618	Wiper Motor, Rear
410	Clutch Disc	619	Headlamp Motor
412	Transfer Case Assembly	620	Wiper Motor, Windshield
417	Clutch Master Cylinder	621	Wiper Transmission
418	Clutch Slave Cylinder	629	Electrical Switch
420	Transfer Case Motor	633	Ignition Switch

430	Drive Shaft, Front	634	Convertible Top Motor
431	Drive Shaft, Rear	635	Convertible Top Lift
434	Axle Assembly, Front	642	Electric Door Motor
435	Axle Assembly, Rear	655	Temperature Control
440	Carrier Assembly	674	Radiator or Condenser Fan Motor/Assy
444	Differential Assembly	675	Radiator
445	Ring Gear and Pinion	677	Heater Assembly
447	Axle Shaft	679	Air Conditioner Condenser
475	Rear Independent Suspension Assy	682	Air Conditioner Compressor
308	Timing Cover	684	Air Conditioner Compressor Clutch
680	Air Conditioner Evaporator	318	Engine Oil Cooler
317	Intercooler	676	Heater Core
408	Bell Housing	319	Air Cleaner
590	Electronic Engine Control Modules	325	Fan Blade
591	Electronic Chassis Control Modules	327	Exhaust Manifold
437	Axle Housing	329	Intake Manifold
477	Suspension Cross member/ K-Frame	336	Air Flow Meter
500	Frame	638	A/V Equipment (formerly Radio)
594	Info/GPS/TV Screen	610	Coil

The Following Parts will be considered **Airbags** and should be handled/graded according to the ARA Protocol.

253	Airbag

The Following Parts will be considered **Cosmetic** and should be graded according to the Cosmetic Grading Standards

251	Dash Panel

The Following Parts will be considered **Glass** and should be graded according to the Glass Grading Standards

270	Windshield Glass	279	Door Vent Glass, Rear
275	Back Glass	280	Door Vent Glass, Front
277	Door Glass, Front	284	Quarter Glass
278	Door Glass, Rear	288	Roof Glass

The Following Parts will be considered **Lights** and should be graded according to the Lights Grading Standards

114	Headlamp Assembly	168	Side Marker Lamps, Rear
116	Front Lamp	176	High Mounted Stop Lamp
166	Tail Lamp	630	Headlamp Door/Cover

The Following Parts will be considered **Mirrors** and should be graded according to the Mirrors Grading Standards

128	Side View Mirror

The Following Parts will be considered **Wheels** and should be graded according to the Wheel Protocol & Grading Standards

560	Wheel	570	Wheel Cover

Appendix C: Calculation Intermediates

Estimated Energy Cost for Mining

Mine Estimate	Tons produced	Fuel (gallons a year)	kWh per year
Iron	13,155,000.00	2800000.00	41802720.00
Aluminum	2,250,000.00	858480.00	11250000.00

Estimated Energy Cost of Producing Metals

Low estimate (MJ)	High Estimate (MJ)	Type
172,000,000,000.00	450,000,000,000.00	Steel (virgin)
17,400,000.00	43,500,000,000.00	Steel (reclaimed)
113,400,000,000.00	153,800,000,000.00	Aluminum (virgin)
11,460,000,000.00	17,800,000,000.00	Aluminum (reclaimed)
24,000,000,000.00	30,000,000,000.00	Iron
Low estimate (kWh)	High estimate (kWh)	
47,777,777,777.78	125,000,000,000.00	Steel (virgin)
4,833,333.33	12,083,333,330.00	Steel (reclaimed)
31,500,000,000.00	42,722,222,220.00	Aluminum (virgin)
3,183,333,333.33	4,944,444,444.44	Aluminum (reclaimed)
6,666,666,666.67	8,333,333,333.33	Iron
89,132,611,111.11	193,083,333,327.78	Total (kWh)
Low	High	
69,049,070	149,577,404	Carbon Footprint (tons)

Manufacturing Cost

kWh/year	Carbon Footprint(tons/year)	Homes
11600000000	8,986,264	1,203,810

Carbon Footprint of US Car Production in 2015

	Low Estimate of Carbon (Tons)	High Estimate of Carbon (Tons)
Mining	59,813.00	59,813.00
Processing	69,049,070	149,577,404
Manufacturing	8,986,264	8,986,264
Total	78,095,147	158,623,481
Per car	6.507928917	13.21862342