Resources, Conservation & Recycling 150 (2019) 104382

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Estimating increasing diversity and dissipative loss of critical metals in the aluminum automotive sector

Ayomipo Arowosola[a], Gabrielle Gaustad[b,*]

[a] Golisano Institute for Sustainability, Rochester Institute of Technology, United States
[b] Inamori School of Engineering, Alfred University, United States

ARTICLE INFO

Keywords:
Circular economy
Critical metals
Aluminum
Lightweight

ABSTRACT

As the demand for and consumption of products and services grow in the US, so does the concern for sustainable material usage. In the automotive industry, major sustainability issues revolve around advocating for improved fuel economy and the incorporation of materials with higher recyclability in order to reduce greenhouse gas (GHG) emissions. A popular strategy to achieve this in the automotive industry is light-weighting. Many studies in this field are focused on the environmental benefits of light-weighting, that is, how replacement of traditional steel in the automotive industry with aluminum, for instance, will help reduce the amount of CO_2-eq emissions in the environment. The increasing use of aluminum in the industry for differing automotive applications broadens the range of alloying elements. Unfortunately, many of these elements are dissipatively lost and also deemed critical. Furthermore, some of the alloying elements accumulate as tramp (unwanted) elements in the secondary aluminum stream, hence posing as a barrier to effective recycling, thus leading to material and economic losses. We quantified the material losses and analyzed the economic losses attributed to the dissipation of critical metals and also examined the attendant accumulation of tramp elements in the recycled aluminum stream. Our results indicate that to achieve a more circular economy requires investment and further development of a) operational blending and batching strategies that comprehend alloying additions and the inherent variability of their actual composition, and b) economically feasible material identification and sorting technologies that will help in abating these material losses and associated economic losses.

1. Introduction

Among sectors in the United States, the transportation sector contributes the most to greenhouse gas emissions (USEPA, 2018b) at 28%. Data from 2009 to 2016 show about a 6% increase in emissions from the transport industry (USEPA, 2018a). Emissions from light vehicles account for over 60% of total emissions from the transport sector (USEPA, 2018c), but the trend observed from 2009 to 2016 show that the contribution to total emissions by light vehicles is on a gradual decrease. This decrease is due to a complex mix of market dynamics, demographics, and technological change; one such technological change that may be contributing is the move toward lightweighting strategies. Lightweighting, in very simple terms, means the replacement of traditional steel structures in vehicles with lighter materials like aluminum, magnesium, plastics, and composites. In North America, aluminum is a top choice material for lightweighting as it has the potential to reduce vehicle weight by 20–30% compared to steel (Miller et al., 2000). Researchers estimate that every 10% savings in curbside weight results in a 5–10% improvement in vehicle fuel economy (Cheah, 2010; Miller et al., 2000). While this contributes to abating tailpipe emissions, aluminum production is very energy intensive and has an emission factor (9.45 kg CO_2-eq/kg Al) of about 4 times that of steel (2.2 kg CO_2-eq/kg steel) (Kim et al., 2010). On the other hand, aluminum production from scrap (secondary aluminum production) has an emission of about 0.9 kg CO_2-eq/kg Al, so to justify lightweighting with aluminum, efficient aluminum recycling is necessary, where there is little dependence on primary aluminum.

Aluminum is used in a wide range of vehicle parts ranging from heat exchangers to closures. Each part will require unique functional properties for these differing automotive applications and therefore include a range of alloying elements. The key alloying elements will differ by alloy family as shown in Table 1, but these additions are copper, manganese, silicon, magnesium, zinc, and tin. The alloy families are called series with 4-digit nomenclature (for the wrought alloys; the cast alloys have 3-digit nomenclature), such that 1XXX is the 1000 series, 2XXX is the 2000 series, etc. The first digit in the series signifies the

* Corresponding author.
E-mail address: gaustad@alfred.edu (G. Gaustad).

https://doi.org/10.1016/j.resconrec.2019.06.016
Received 16 November 2018; Received in revised form 30 May 2019; Accepted 12 June 2019
Available online 17 July 2019
0921-3449/ © 2019 Elsevier B.V. All rights reserved.

Table 1
Aluminum Association alloy family designations showing major alloying elements for each series.

	Wrought	Cast
Pure Al 99% or higher	1XXX	1XX
Major alloy elements:		
Copper	2XXX	2XX
Manganese	3XXX	
Silicon	4XXX	4XX
Magnesium	5XXX	5XX
Magnesium & Silicon	6XXX	
Zinc	7XXX	7XX
Other & Specialized	8XXX	9XX
Tin		8XX
Si + Cu + Mg		3XX

major alloying element as identified in Table 1, the third and fourth digit are arbitrary numbers that identify the specific alloy and the second digit indicates a special modification to the specific alloy. For example, alloys 2024, 2124, 2324, 2424, 2524, 2624, 2724 and 2824 are aluminum alloys that have copper as the major alloying element, but alloys 2124 to 2824 are modifications of alloy 2024. Same is true for alloys 2018, 2218 and 2618. These modifications may be in the amount of the major alloying element or amounts of other alloying elements. These may include nickel, lead, chromium, titanium, bismuth, vanadium, lithium, scandium etc. (European Aluminium Association, 2002).

Many of these alloying elements are considered critical. Critical metals are those metals that are highly demanded, strategic, have few or no known substitutes or replacement and/or are vulnerable to supply disruptions (National Research Council, 2008). Chromium is an example of a critical metal used in metallurgical applications for its excellent resistance to corrosion and high temperature properties (Barnhart, 1997). Chromium, is often included as critical (Nuss et al., 2014) due to its high demand and lack of substitutes for most major industrial applications. Vanadium, like chromium, is also widely used in metallurgical applications for added strength properties. Approximately 80% of its global production is as a companion metal, i.e. a byproduct of other base (or host) metals, like iron and bauxite (Nassar et al., 2015; Nuss et al., 2014). In recent years, the U.S. has solely relied on imports of vanadium whose production has been in very few countries (U.S. Geological Survey, 2018). Thus, vanadium is one of such elements deemed critical based on its supply risk.

While a handful of organizations have differing lists of critical metals (Department of the Interior, 2018; European Commission, 2017), the National Research Council (NRC) (National Research Council, 2008) defines the criticality of metals based on their "importance in use" and "potential supply restrictions". Recycling restriction based on stock and recyclability has also been used as a measure of criticality (Hatayama and Tahara, 2015)

Lightweighitng, as a solution to improving fuel economy (Brooker et al., 2013) can create complexities for circular economy strategies, particularly recycling, in the automotive industry. Continuous recycling can result in the accumulation of tramp or unwanted elements in the aluminum stream (Gaustad et al., 2010), thereby resulting in secondary aluminum that is rich in impurities. In most cases, if aluminum is being recycled into aluminum this would be considered closed loop, however, in practice the aluminum is not going into the same type of alloy in most cases. This then causes reduced utilization rates of secondary aluminum since metal batches have to be diluted with primary aluminum in order to meet required specifications of the desired new alloy. With their dissipative losses and their accumulation in the aluminum stream, an open loop is observed with these alloying elements and thus loss of material, as well as loss of embodied energy, both alluding to economic losses. Recycling end of life vehicles (ELV) is a well-established and profitable industry but is mostly suited to steel-structured vehicles. The process starts out with disassembling the vehicle to separate hazardous fluids from reusable components and valuable parts. Next, the materials are typically shredded to liberate valuable materials and then separation techniques such as eddy currents are employed to move scrap into different material streams, ferrous, non-ferrous (metallic non-ferrous) and automotive shredder residue (non-metallic non-ferrous) (Cui and Roven, 2010). These preparation stages of recycling ELVs (disassembly and shredding) are roughly 75% efficient in the US (Boon et al., 2000). Typically, aluminum in processed ELVs are bulky castings that are easily removed from the vehicles and are comparably easily recyclable into castings used in automotive industry, the largest consumer of secondary aluminum (Modaresi and Müller, 2012). In the near future, aluminum intensive vehicles will have more wrought alloys in the form of sheets, forged alloys and extrusions. With the current recycling technologies, recycling efficiencies are bound to reduce due to:

1 Incompatibility between existing recycling technologies, geared towards aluminum cast alloy recycling, and next generation vehicles comprising of more wrought alloys than cast alloys.
2 Surplus scrap that will be created with a reduced demand in automotive castings, the largest consumer of secondary castings (Modaresi and Müller, 2012). Unlike cast aluminum alloys, wrought aluminum alloys have tight specification allowances (Cui and Roven, 2010) that limit their production from secondary aluminum. Secondary aluminum has a wide range of impurities like Fe, Si or Zn in varied amounts, present as a result of intentional alloy modification or introduced along the way through applications of mechanical processes.

The historic and futuristic use of aluminum and its alloys as lightweight materials have been analyzed and predicted respectively by Ducker Worldwide, a global consultancy firm that helps companies and industries strategize and make decisions based on intensive data analyses. The analysis shows an increasing trend as pressure on original equipment manufacturers (OEMs) to increase fuel economy continues (Cheah and Heywood, 2011; Ducker Worldwide, 2017). If this trend is to continue as predicted (see Fig. 1), then these critical metals, and other alloying elements need to be tracked to inform of the different avenues to possibly close the loop and thus, reduce the negative economic impact. This research quantifies these material flows to a) inform the dissipative losses of these economically important alloying elements, and b) inform the recycling process to potential challenges of increased diversity of alloying additions. While losses as energy expended may not be easily quantified, economic losses in terms of material input can be quantified in dollar values based on the market price of these materials. While quantifying the economic loss requires the knowledge of the current market price, quantifying the dissipative losses requires a material flow analysis (MFA) to understand the inflow and outflow of aluminum and its alloying elements. A key barrier to performing an MFA for this sector is that most data sources track total aluminum by production type (wrought, cast, extruded, etc.) (U.S. Geological Survey, 2018) and not by specific alloys, so it is quite difficult to quantify the alloying elements that are a part of these material flows. Another barrier is the lack of readily available data specifying actual automotive components and the alloys used.

Previous studies have looked into the use of rare earth metals and platinum group metals in the catalytic converters of internal combustion vehicles (Alonso et al., 2012; Nansai et al., 2014; Peiró et al., 2013); however, there is a lack of work examining other critical metals contained in automotive. While the amount of critical metals present in a lightweight vehicle might seem relatively negligible, the aggregate mass flow, considering total lightweight vehicle production in North America, possibly has an impact on the demand of these critical metals.

Graedel et al. (2011), discuss the recycling rates of metals and mention barriers to closing the open circle of material flow, particularly

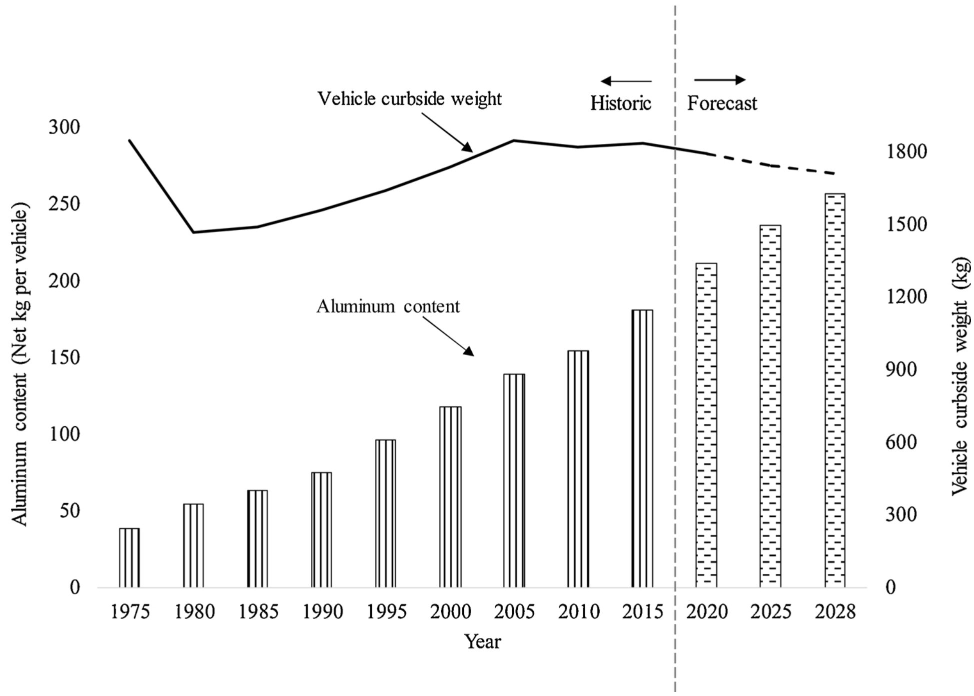

Fig. 1. Average vehicle curbside weight (US Environmental Protection Agency, 2018) and aluminum use in vehicles in North America (Ducker Worldwide, 2017).

in consumer products like vehicles. These include complicated product designs that discourage disassembly, uncontrollable material flows because of high product mobility, lack of knowledge on the attributed economic losses, and lack of recycling infrastructures and updated recycling technologies.

Beyond creating awareness on resource loss, achieving a closed loop for critical metals is faced with other challenges. As discussed by Zimmermann and Gößling-Reisemann (2013), these critical metals are dissipatively lost. Their dissipation occurs all the way from cradle-to-grave, i.e. from their production to their disposal. In-use dissipation and a lack of robust recycling technologies accounts for the loss of over 50% of annual input flow of critical metals. They also discuss the different types of dissipation exhibited by critical metals at their different lifespan stages – Dissipation into the environment (type A), into other material flows (type B) and into landfills (type C). While type A is the most difficult to recover the metals from and poses the most health hazard, type B is the most dominant of all the categories as more critical metals are used as alloying elements in the enhancement and modification of properties of other materials. Type B dissipation might not be as difficult as type A dissipation in terms of metal recovery, but the critical metals dissipated into other material streams are in such small amounts that it is not economically feasible to recover them. Recycling of the host material, on the other hand, is a common practice across industries, including the automotive industry. Unfortunately, continuous recycling of the host materials result in the accumulation of these alloying metals as tramp “unwanted” elements in the host material stream. Tramp element accumulation is a problem in many recycled material streams like steel, plastic, copper, etc.; however due to thermodynamics, aluminum has the most accumulation challenges with magnesium, nickel, lead, chromium, iron, vanadium, silicon, copper and zinc cited as some of the possible tramp elements that increase with the recycling of aluminum (Gaustad, 2009). Copper and zinc (listed above) and other alloying elements like manganese, tin, titanium and bismuth used in the aluminum industry (European Aluminium Association, 2002) are also seen to exhibit different amounts of in-use dissipation, ranging from approximately 1%–20 % by mass of the element dissipated in-use (Ciacci et al., 2015).

With the dissipative characteristics of these alloying elements and their accumulation as tramp elements, continuous recycling hits a barrier where the material continuously gets downcycled until it is eventually disposed of. So ultimately, a type B dissipation, over time, ends up being a type C dissipation. Along with other material flow analysis results, this paper aims to quantify and analyze the dissipative losses of critical metals and the accumulation of tramp elements in the recycled aluminum stream as well as the attributed economic losses.

2. Methodology

In order to quantify dissipative losses of critical alloying elements in automotive aluminum, a material flow analysis that included resolution to the compositional level was conducted. Different aluminum vehicle parts employed for lightweighting were compiled from a variety of sources. Scenarios were built from assumptions on which specific alloys were the most likely to be used for each vehicle part application. Forecasts for light vehicle sales in North America were used to extrapolate total materials usage and resultant dissipative losses as shown schematically in Fig. 2.

2.1. Compositional characterization

Using the Aluminum Association’s teal books, we characterized the maximum and minimum potential elemental composition according to the specification for each alloy, and by extension, each aluminum vehicle part. The total aluminum content for a representative lightweight vehicle were derived from Ducker (Ducker Worldwide, 2017); this analysis provides historical aluminum content as well as future projections. Vehicle parts that were likely to be aluminum alloys were identified from industry and academic literature; these potential aluminum car parts and alloys were combined to create scenarios detailed in Section 2.3. As shown in flow of Fig. 2, first the total amount of aluminum in a lightweight vehicle is identified, then the vehicle parts made of aluminum are identified. For example, in a generic North American lightweight vehicle, 45% of the aluminum use is in the cast engine and cylinder heads. Then, the typical alloys used for these parts are identified. For engine castings, the alloy can either be alloy A380 or alloy A319. At this point, scenarios are developed as the alloy selection

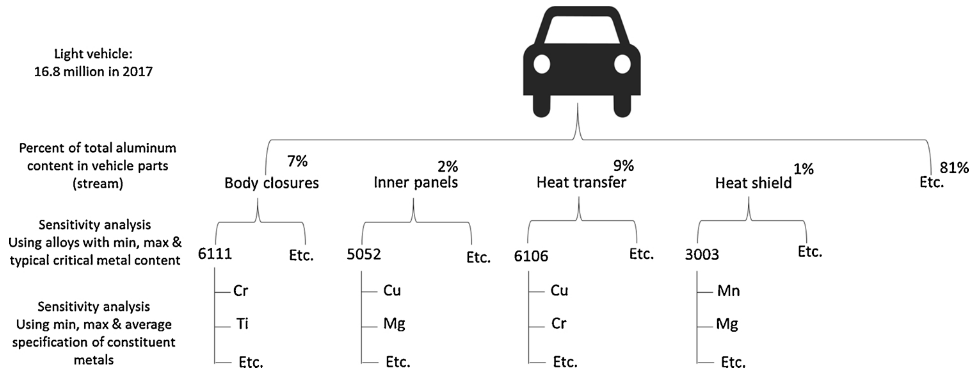

Fig. 2. Schematic diagram of methodology.

will vary for different makes and models of vehicles. If silicon was the element of interest for this case, the Aluminum Association indicate a specification window of 7.5%–9.5% weight percent for A380 and 5.5%–6.5% weight percent for A319. We would then select the minimum specification of 7.5% for Si in A380 (and subsequently for all constituent metal in A380) and calculate the total critical metal content in A380. Same would be done for A319. Whichever one of A380 and A319 has the lesser total critical metal content is selected as the minimum content scenario. The same selection process is followed for maximum content scenario but this time, the maximum specification for each constituent metal is used and the alloy with the greater total critical metal content is selected as the maximum content scenario.

2.2. Material flow analysis

Material Flow Analysis (MFA) is a tool used to quantify the flows and stocks of a material, substance or product. Depending on defined parameters, it considers processes such as extraction, fabrication, waste, transformation, use, and end of life (EOL), i.e. reuse, recycling and/or disposal. There are two (2) approaches to carrying out an MFA: a) the top down and b) the bottom up approach. The top down approach estimates the material in stock by taking into account, the net flows (inflow less outflow) over a defined period of time; while the bottom up approach estimates the material in stock by identifying all relevant material streams and summing up the material in each stream (Laner and Rechberger, 2016). For this research, i.e. to analyze and quantify the amount of each alloying element present in each alloy specification, we used a combination of both methods to build a model where we identified two sets of material streams; the vehicle parts that contain aluminum and the aluminum alloys that contain the constituent elements. Fig. 2 gives a schematic of the approach where car parts like body closures, inner panels, etc. were identified to contain aluminum alloys in which about 7% of total aluminum content of a car is in the body closure. Also, each car part was found to be made from different aluminum alloys, e.g. the body closures could be made of alloy 6111, 6010, etc. Finally, each alloy is characterized based on its constituent element. For instance, alloy 6111 contains chromium, titanium, etc.

2.3. Scenario analysis

The critical metals considered in this study were manganese, magnesium, chromium, titanium, tin and vanadium (Department of the Interior, 2018; Moss et al., 2013; Wagstaff, 2018). The total critical metal content in a typical lightweight vehicle was calculated by summing up the amounts of each of the listed critical metals above that are present in the aluminum alloy employed in the car part. Two extreme scenarios and a midpoint scenario as shown in Table 2, were analyzed based on the range of specification provided by the Aluminum Association for each alloy and the multiple alloys that can be utilized for a car part:

Table 2
Description of scenarios explored for sensitivity analysis.

Aluminum in vehicle parts [16]		Alloys used in Sensitivity Analysis		
Vehicle part	Percent content of total aluminum in vehicle (%)	Max CM using max spec limit	Min CM using min spec limit	Typical Alloy using midpoint of spec range
Engine & Cylinder heads	30	A380	A380.2	A380.2
Trans & Driveline	21	A380.2	A380.2	A380.2
Heat Shields	1	5182	1050	1050
Heat Exchangers	9	5049	1050	3003
Wheels	11	6082	A356	6082
Steering system	5	6082	7108	6082
Suspension Parts	3			
(knuckles)		6013	6013	6013
(control arms)		6082	6082	6082
Brake System	2	F3N20S	F3N20S	F3N20S
Body Closures	7	6010	6111	6061
Body frame & Inner Panels	2	5182	5052	5182
Collision Mgt.	7	6013	6013	6013
Cradles, Frames	2	5182	5182	5182
Total	**100**			

- Alloy with maximum critical metal (CM) content using maximum specification limit of alloy constituents
- Alloy with minimum critical metal (CM) content using minimum specification limit of alloy constituents
- Typical alloy used in the industry using midpoint of specification range of alloy constituents

Where there is no specification range for a constituent metal, the value specified was used across the three scenarios.

While a synthesis of the literature provided an average of aluminum parts by weight in lightweight vehicles, the proportion can differ widely for each make and model. Therefore, a general case was used to represent an average light-weight passenger vehicle in North America. A specific make and model case study was also carried out on the 2015 Ford F-150 pick-up truck. The F-150, known for being aluminum intensive compared to the average vehicle, has a curb weight in the range 4069 lb (1846 kg) – 5697 lb (2584 kg). Depending on the model, the engine size ranges from a 2.7 l (V6) to 5.0 l (V8) with in-city fuel mileage ranging from 15mpg – 20mpg and highway fuel mileage ranging from 18mpg – 26mpg.[1] The case study analyzes the differing amounts of critical materials present in the aluminum sheet alloys used as skin alloys for closures and outer panels as a function of time from 1962 to 2005 Chappuis (2019). This case study was selected as the Ford F-150 has garnered a significant amount of publicity for the design

[1] 2019 F-150| fleet.ford.com.

Table 3
Typical Alloys in the Automotive Industry (European Aluminium, 2019; Fridlyander et al., 2002; Miller et al., 2000; Staley and Lege, 1993; Staley et al., 2018).

Body & Inner Panel	Body Closures	Heat Exchangers	Heat Shields	Misc Engine
2008, 5030, 5052, 5182, 5454, 6009, 6016, 6111	2008, 2036, 6009, 6016, 6010, 6383, 6061, 6111	6060, 6061, 6063, 6106, 5049, 7072, 1145, 4047, 4004, 4045, 4343, 3003, 8079, 6006, 1200, 1050, 1100	1056, 3003, 5052, 5182	226, AlSn20Cu, AlZn5Bi4
Cradles & Frames	**Wheels**	**Steering system**	**Fuel system**	**Engine/Cylinders**
5182	356, 6081, 6061	6082, 7108, 7021	6063, 3103, 5049, 5754	380, 319, Al-Si
Collision	**Brake System**	**Suspension parts**	**Trans**	**Pistons**
6013, 7021, 7029	359 or 360 +SiC	AlSi7Mg, 6013, 6082	380.2	4032

team's decision to go with an aluminum body compared to traditional high-strength steel designs for pick-up trucks. The skin alloys analyzed for each year in review corresponds to the skin alloys registered as automotive skin alloys for that year.

3. Results and discussion

3.1. Identifying aluminum vehicle parts

Table 3 lists the various aluminum alloys used in each aluminum-containing vehicle part. The difficulty in performing an MFA of this scope is seen in i) the various alloy series that can be present in a vehicle part and ii) the implicit uncertainty created by the content specification range of each alloying element in the alloy. This can be illustrated by considering an example from literature (Gaustad, 2009); 2 aluminum manufacturers, company A and company B, each produce alloy 6061, a very common automotive sheet alloy. Table 4a shows the AA guidelines to the minimum and maximum amount specification of individual alloying elements. "Other each" is the maximum allowable amount for any other individual alloying element not listed and "other total" is the maximum allowable amount for all of these other unlisted alloying elements combined. Company A has a customer whose application of the alloy requires most of the alloying elements to be near the maximum specification while company B has a customer that requires the alloy to be produced at minimum specification. While the resulting alloys from both companies are designated as 6061, Table 4b shows that their composition differs as much as observing a 3% difference in total aluminum content.

The above illustration shows the possible difference in amount of constituent metals in a particular alloy. Further into the uncertainty of constituent metal amount, is the different possibilities of alloys used. A typical heat exchanger in a lightweight vehicle could be made from nearly any of the alloying families, which have different major alloying elements as previously reported in Table 1.

The analysis in Fig. 3 shows that for a typical heat exchanger, if the assumption is that it is made of 1050, there would be very few alloying elements with a total of 0.04 kg/vehicle of critical metals. However, the assumption of an alloy like 5049 means that the magnesium content would be quite high. Alloy 5049 would result in 0.70 kg total critical metals per vehicle. Assuming 17 million lightweight vehicles produced per year, this would mean a range of about 700 metric tons to 12,000 metric tons of total critical metals resulting from just variations in heat exchanger assumptions.

Table 4a
Aluminum Association weight percent (wt %) specification for 6061.

Alloying Elements	Min	Max
Si	0.4	0.8
Fe	0	0.7
Cu	0.15	0.4
Mn	0	0.15
Mg	0.8	1.2
Cr	0.04	0.35
Zn	0	0.25
Ti	0	0.15
Other Each	0	0.05
Other total	0	0.15

Table 4b
Comparison of alloy 6061 specifications (wt %) across companies A and B.

Alloying Elements	Company A	Company B
Si	0.8	0.4
Fe	0.7	0
Cu	0.4	0.15
Mn	0.15	0
Mg	1.2	0.8
Cr	0.35	0.04
Zn	0.25	0
Ti	0.15	0
Ni	0.05	0
Ga	0.05	0
V	0.05	0
Total alloying elements	4.15	1.39
Aluminum content	95.85	98.61

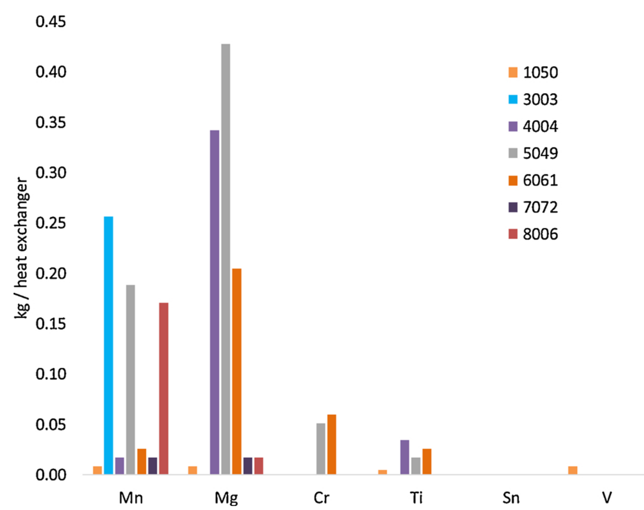

Fig. 3. Diverse range of elemental amount in heat exchanger alloys.

3.2. Estimating critical metal content per lightweight vehicle

Individual variation in alloy for lightweight vehicle parts was synthesized into scenarios to explore the total critical element content per typical lightweight vehicle; results were explored for each constituent metal. Results (Fig. 4) show that total critical metal content per lightweight vehicle is in the range of about 0.6 kg to 3.6 kg per vehicle. It

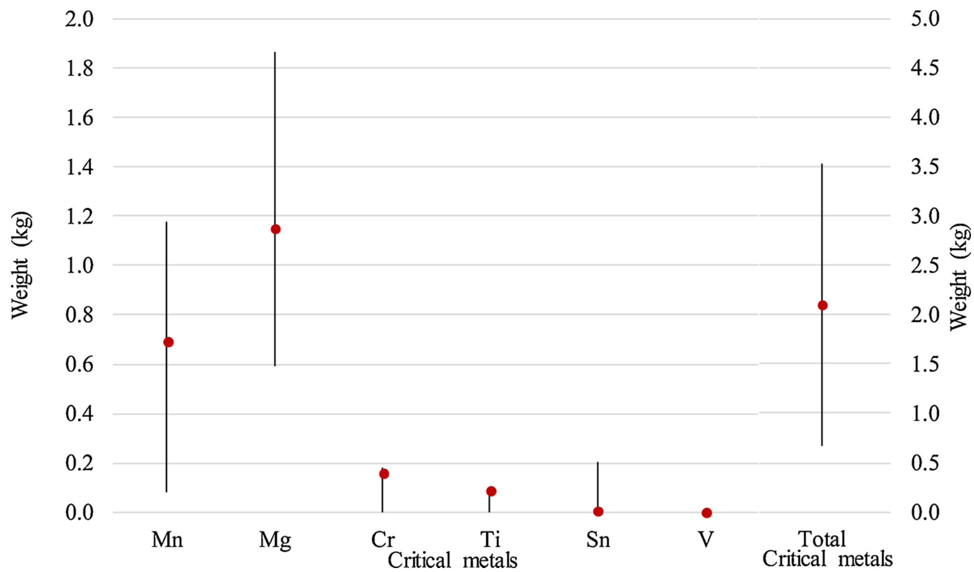

Fig. 4. Predicted range of critical metal content per representative lightweight vehicle; Total critical metals on right axis.

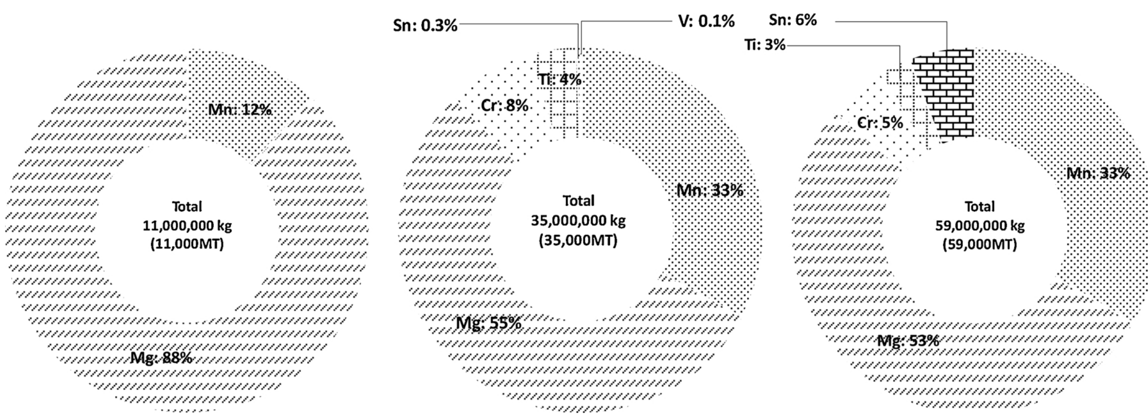

Fig. 5. Total critical metal content distribution by alloying element showing the 3 scenario analyses; (from left to right) minimum, average and maximum.

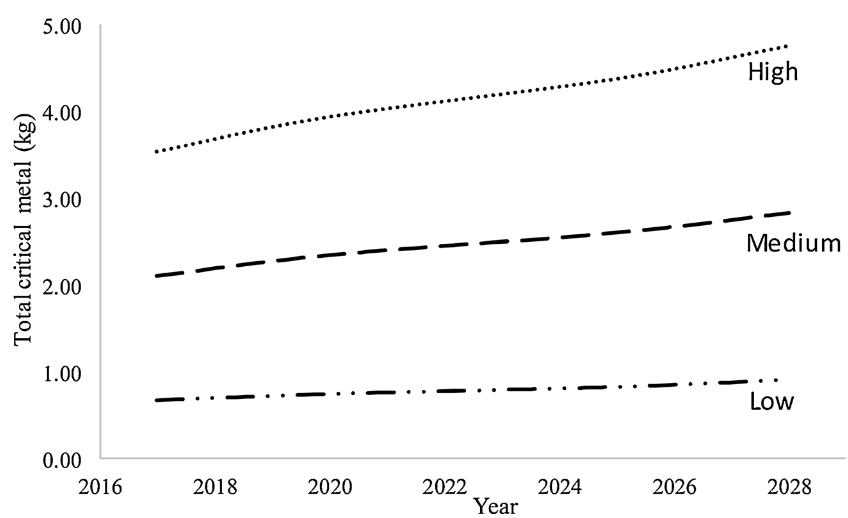

Fig. 6. Trend in total critical metal content per vehicle across scenarios.

also shows results for each critical metal across the three scenarios that were described in the methodology. The top of each high-low line signifies the maximum critical metal content scenario, the bottom signifies the minimum critical metal content scenario and the red marker signifies the typical scenario. Translating this to total North America lightweight vehicle production of 16.8 million for 2017 (Petit, 2018), and using the typical scenario value of approximately 2.0 kg critical metal per vehicle, approximately 35 Gg (35,000 metric tons) of critical metals were used in lightweight vehicle production in 2017. Magnesium makes up more than half of this amount, 19 Gg (19,000 M T) with

Table 5a
Critical metal content distribution by part as fraction of total critical metal content per vehicle.

Al content per vehicle		Typical Alloy	Critical metal content (%)
Parts	kg		
Wheels	20.9	6082	19
Collision Mgt.	13.3	6013	11
Suspension-Knuckles	3.7	6013	11
Body Closures	13.3	6061	10
Heat Exchanger	17.1	3003	10
Body frame & inner panel	3.8	5182	9
Steering	9.5	6082	9
Cradles, Frames	3.8	5182	9
Engine & Cylinder heads	57	380.2	5
Trans, Driveline	39.9	380.2	2
Suspension-Control arm	2	6082	2
Brake system	3.8	360 + SiC	2
Heat Shields	1.9	1050	0
Total	**190**		**100**

manganese at 12 Gg (12,000 M T), chromium at 3 Gg (3000 M T), and titanium, tin and vanadium at 1 Gg (1000 M T), 0.1 Gg (100 M T) and 0.02 Gg (20 M T) respectively as shown in Fig. 5. Fig. 6 shows our sensitivity analysis depicting the increasing trend of total critical metal content per vehicle across the years based on the forecasted aluminum content per vehicle. We also observe an increasing range of uncertainty from 0.6 kg (minimum case scenario) to 3.6 kg (maximum case scenario) per vehicle in 2017 to about 0.91 kg (minimum case scenario) to 4.75 kg (maximum case scenario) in 2028.

The result is further resolved into critical metal content by part. Table 5a shows the critical metal content per part as a fraction of total critical metal content in the vehicle. Here, the most critical metal content is found in the wheels, followed by the collision management parts and suspension knuckles. Table 5b refines the total critical metal content into each critical metal under study. For example, in the body frame and inner panels with 5182 as the typical aluminum alloy, there is a total of 192 g of critical metal content consisting of 13 g of manganese, 171 g of magnesium, 4 g of chromium and 4 g of titanium. Another result read off here is the distribution of each critical metal across the aluminum parts in the vehicle. Take titanium as an example; approximately 87 g of titanium is used per lightweight vehicle and most of it is in the wheels and body closures.

While some of the critical metals are small in amount compared to the major alloying elements, they are much higher in value. Potential economic impact resulting from dissipative losses were calculated based on reported prices of each metal and are shown in Table 6.

Table 5b
Individual critical metal content distribution by part; values have been rounded-off.

Parts	Typical Alloy	Aluminum content (g)						
		Mn	Mg	Cr	Ti	Sn	V	Total
Wheels	6082	146	188	52	21	0	0	408
Collision Mgt	6013	67	133	13	13	0	0	226
Suspension-Knuckles	6013	67	133	13	13	0	0	226
Body Closures	6061	20	133	47	20	0	0	219
Heat Exchangers	3003	214	0	0	0	0	0	214
Body frame & inner panel	5182	13	171	4	4	0	0	192
Steering	6082	67	86	24	10	0	0	185
Cradles, Frames	5182	13	171	4	4	0	0	192
Engine & Cylinder heads	380.2	57	57	0	0	0	0	114
Trans & Driveline	380.2	0	40	0	0	0	0	40
Suspension-Control arm	6082	14	18	5	2	0	0	39
Brake system	360 + SiC	13	23	0	0	6	0	42
Heat Shields	1050	1	1	0	1	0	1	3
	Total	691	1153	162	87	6	1	2100

Table 6
Market price and value of alloying elements used in the aluminum sector of the automotive industry (U.S. Geological Survey, 2018); *Price of manganese and chromium obtained from Fastmarkets AMM: Daily Metal Price (October 19, 2018).

	Amount 2017 production (million kg)	Price ($/kg)
Mn	11.61	2.53*
Mg	19.37	4.78
Cr	2.72	11.20*
Ti	1.95	8.60
Sn	0.10	20.78
V	0.02	11.56
Total	35.28	

Results show that the dollar value from the critical metals used in total lightweight vehicle production in 2017 is approximately 167 million USD. Fig. 7 compares the weight of each critical metal to their value (dollars). Results show that tin has the highest value to weight ratio, followed by vanadium, chromium, titanium, magnesium and manganese. These values represent a maximum potential loss and these elements will not be fully lost in certain recycling loops as some blending algorithms will comprehend the alloying elements present and take advantage in the batch recipe, although dilution is likely to still occur (Gaustad et al., 2007). However, down-cycling is also very likely to occur in other recycling systems for example wrought aluminum alloys will be used to produce cast aluminum alloys or specialty steels will be recycled into rebar (Brooks et al., 2019). For these cases, the functionality of these elements will indeed be fully lost.

3.3. Critical metal usage over time: Ford F150 skin alloy case study

Increasing the aluminum content in vehicles is increasing the total alloying element content in a lightweight vehicle. Getting data to illustrate this is challenging as most original equipment manufacturers (OEMs) do not release specific alloys used in specific makes and models. However, some data are available for the Ford F-150 Chappuis (2019), a vehicle that is widely advertised for its aluminum autobody. Looking at alloy use over time shows that total alloying elements present in the skin alloys (closures) of the pick-up truck will increase over time. We show mass forecasts of total alloying elements per F-150 skin alloys over time using five (5) different scenarios: the five different aluminum alloys still in use as skin alloys.

Each year's data shown in Fig. 8 below correspond to the different alloys that were registered as skin alloys. From 1962 to 2005, ten (10) alloys – 6005, 2036, 6009, 6010, 6111, 6014, 6016, 2008, 6022 and 6451 – were registered, in that order, as automotive skin alloys and only five (5) of them – 6005, 6014, 6016, 6022 and 6451 – are still in use at present (scenario on skin alloys in use zoomed out). The forecast carried out considered the historic and forecasted amounts of aluminum per vehicle, as well as the mass of aluminum in skin alloys (closures) from the Ducker analysis (Ducker Worldwide, 2017). Historic and forecasted skin alloy data was available for 2016 and 2020 respectively. Data prior to 2016 and after 2020 for skin alloys were extrapolated in proportion to the aluminum content per vehicle corresponding to each year. These data, from 1962 to 2028, were used to calculate the total critical metal content in the skin alloy corresponding to each year. From 2016 to 2020, aluminum content in closures is forecasted to increase by over 100%. This is reflected in the rapid increase in critical metal content across all 5 scenarios from 2016 to 2020.

Though the analysis is based on Ford F150 skin alloys, and the uncertainties involved will differ from one auto manufacturer to the other, the results show that whichever one of the alloys are used in a lightweight vehicle as skin alloys, there is an unavoidable increase in critical metal content over time. While this research work focuses on metals that make up the frame of the vehicle, the authors acknowledge

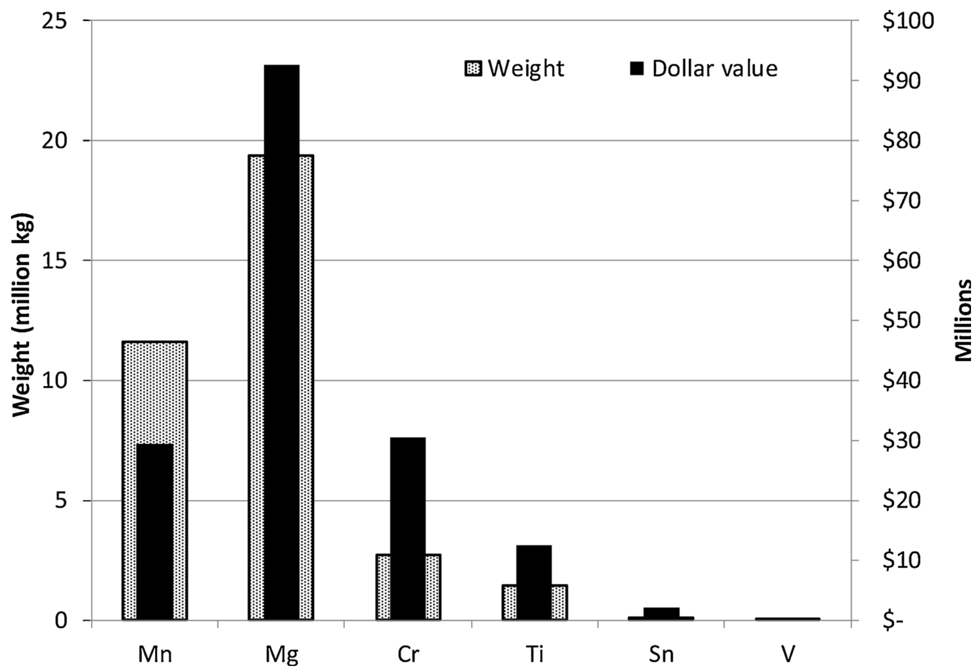

Fig. 7. Weight (million kg) compared to value (million dollars) of individual alloying elements in 2017 in the United States.

that the significant increase of electorincs within the car will also greatly contribute to an increase of overall critical metals contained (Restrepo et al., 2017). The result from the F150 case study can even more so be generalized for lightweight vehicles, seeing that the greatest increase in the projected use of aluminum is seen in the use of aluminum sheets for body closures (Ducker Worldwide, 2017). The result also highlights how choice of skin alloy will impact the degree of critical metal content. This emphasizes how policy could be influential in this space; design for recycling approaches may incentivize one alloy use over another where function remains unchanged. This analysis points to the conclusion that increasing the aluminum content in vehicles (as seen in lightweight vehicles), increases the amount of alloying element (and thus potential tramp elements) and the critical metal content.

Another study in this research sought to analyze the effect of increasing wrought aluminum content in vehicles. The analysis by Ducker (Ducker Worldwide, 2017) show two mass reduction scenarios, where the cast aluminum content is reduced from about 70% to i) about 60% and ii) about 40%. This reduction scenario does not contradict the forecasted trend of increasing aluminum usage in vehicles. It simply captures the current trend of using more wrought aluminum in various vehicle parts and less cast aluminum in engines to continue the lightweighting trend (as cast is much denser than wrought). This is not substitution but a fundamental change in the alloy types used in a typical vehicle (Bayliss, 2019).

Using this scenario, a what-if analysis was created to observe the tradeoffs in increasing the wrought aluminum content from 30% to 70%. This increase is likely to be in the body panels, body closures and bumpers as projected by Ducker (Ducker Worldwide, 2017). Fig. 9 shows the total critical elements with increasing wrought aluminum

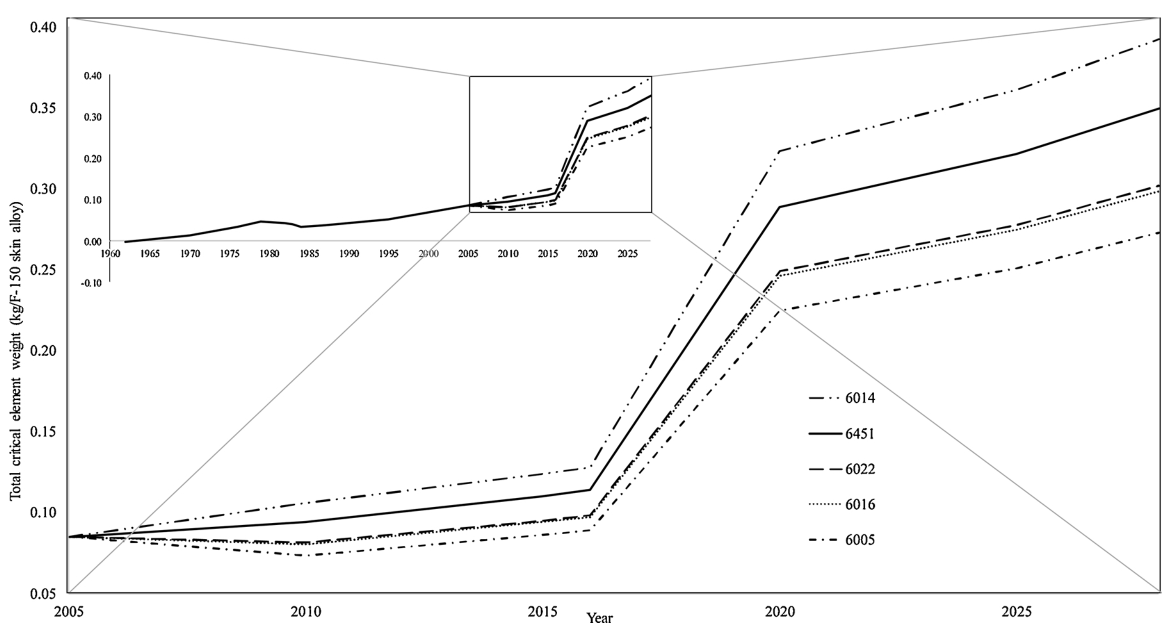

Fig. 8. Increase in total critical element per F-150 skin alloy; 5 scenarios based on alloys currently in use.

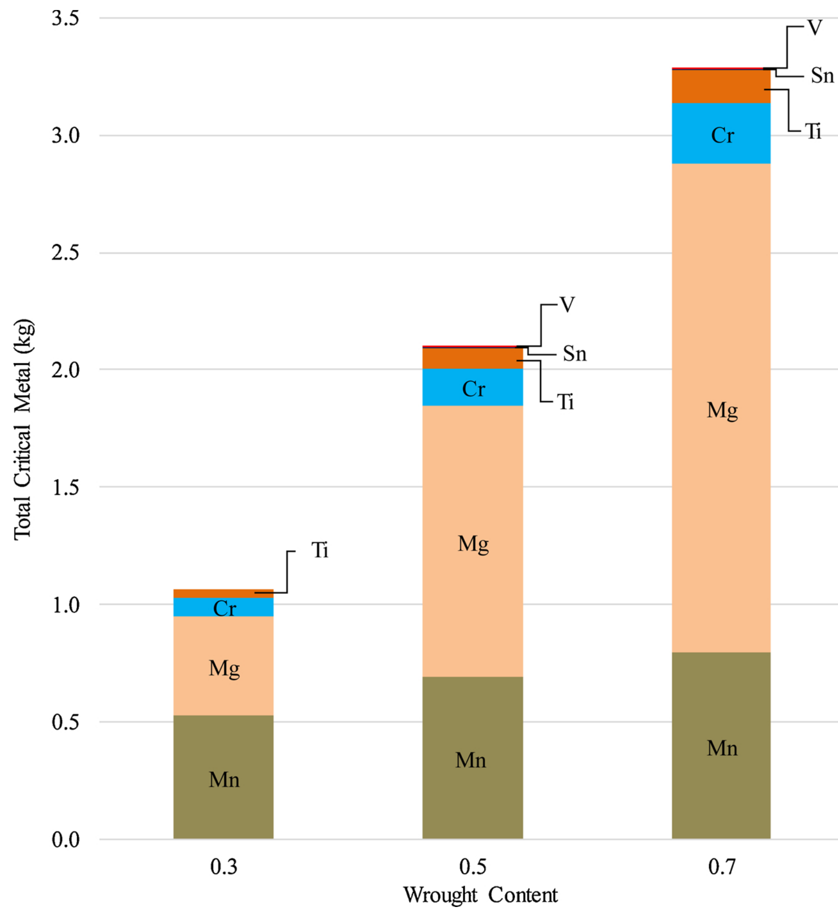

Fig. 9. Relationship between total tramp element and wrought aluminum content.

content. As the trend moves from 30% to 50% wrought content, we see a total critical metal content increase from approximately 1.1 kg to approximately 2.1 kg, and from 50% to 70% wrought content, the total critical metal content increases to approximately 3.3 kg. Also, wrought content growing from 30% to 50% also shows the inclusion of new critical metals (tin and vanadium) introduced as alloying elements. These new critical metals are also present at 70% wrought content. We conclude from this results that increasing the wrought content increases the number of alloying elements used. Of note, is the increase in the diversity of alloying elements, as seen in the inclusion of tin and vanadium at 50% wrought content.

4. Implications and future work

Understanding how to make the automotive materials sector more circular requires quantifying uses and dissipative losses of those materials. Accumulation of alloying elements as tramp elements also negatively impacts recycling of aluminum automotive alloys in the circular economy. This work aimed to bridge a methodological and data gap in doing a material flow analysis of this sector, namely, a lack of elemental resolution of alloying elements in automotive aluminum. This challenge was highlighted by results illustrating the wide range of aluminum alloys present in a lightweight vehicle; the diversity of alloy family designations for specific parts (e.g. heat exchangers) leads to a large range in uncertainty for alloying material content and hence both critical and possible tramp elements; 0.7 kg to about 3.6 kg total critical metal content per representative lightweight vehicle. This may be an opportunity for policy in the automotive sector to push for certain alloy selections to aid in "design for recycling" (Gaustad et al., 2010). In 2017, total lightweight vehicle production was 16.8 million cars which translates to roughly 35 Gg (35,000 MT) of critical metals being utilized. Over 50% of this total was magnesium, the remainder being manganese, chromium, titanium, tin and vanadium in order of magnitude. The automotive aluminum industry is characterized by a non-functional recycling system, so these alloying elements are somewhat functionally lost in that system. Translating this into dollar values, approximately 167 million U.S. dollars are functionally lost in the system. Furthermore, data from USGS (U.S. Geological Survey, 2018) shows that the reliance on import for each of the critical metal analyzed here is on the high side – 100% for manganese and vanadium, 75% for Sn, 69% for chromium and 53% for titanium. Only magnesium has a less than 25% reliance on import. This large reliance on import is one factor for material criticality based on supply risk. In cases where a melt shop is using an advanced blending algorithm or batch plan, the alloying elements in the scrap are more efficiently used and therefore not lost. Sorting combined with positive material identification technologies enables this to be even more efficient. Again, the role of policy here could be influential. In the EU, the End of Life Vehicle Directive requires high targets of recovery for automotive materials driving enhanced recycling. In the US, the solely profit-based recycling infrastructure is unlikely to be incentivized to prevent dissipative losses of alloying elements; dilution and down-cycling will likely continue.

The case study on registered automotive skin alloys used in the Ford F-150 show that newer vehicle models are pushing lightweighting to new levels and thus increasing the magnitude and variety of alloying elements contained in vehicles. This is likely to continue as the use of aluminum sheets for body closures is projected to increase if pressure on increasing corporate average fuel economy (CAFE) standards remains. The strategy for better fuel efficiency through light-weighting will also continue to drive down the automotive demand for castings which contributes to these trends. The trend of less demand for castings will also complicate the automotive aluminum circular economy as castings are a compositionally forgiving sink for recycled aluminum and the largest consumer of secondary aluminum (Modaresi and Müller, 2012).

Results show the dissipative losses of critical metals in these alloys are not insignificant. To achieve a more circular economy and abate these material and economic losses, enhanced recovery techniques will be required (Ciacci et al., 2015; Laner and Rechberger, 2016). Operational strategies like blending models that can make better use of the contained alloying elements instead of diluting those with primary, or downcycling into castings will be necessary (Staley et al., 2018). Technological strategies like improved inbound inspection in yards, positive material identification tools, and spectrographic-based robotic sorting may provide improvements, although the economic feasibility of these approaches will require capturing the value of the contained metals more efficiently than current trend (Moss et al., 2013; Wagstaff, 2018). Specifically, the technological solutions to ensure material identification by alloy would be required to enable blending plans that comprehended specific composition with alloying element resolution.

It should be also be noted that some policy interventions may contribute to this issue. For example, having high recycling targets for automotive (e.g. the European Union End of Life Vehicle Directive) often drives recyclers to put recycled content in the easiest sink possible in order to achieve these targets. A common example in the industry is the use of cast aluminum alloys as sinks for recycling wrought aluminum alloys. This often means dilution with primary to meet compositional specifications or downcycling of alloys into lower value alloys or applications. While both strategies (dilution and downcycling) yield high recycling rates, they: (1) negatively impact resource lost because lower value alloys like castings do not require the high value alloying additions like manganese, nickel, vanadium, etc. so their functional purpose is lost in recycling and (2) contribute to increasing overall emissions because dilution to meet specifications requires the addition of primary aluminum which has nearly 90% more of a greenhouse gas emissions impact than secondary aluminum.

Acknowledgements

The authors would like to acknowledge funding from the National Science Foundation (NSF), through CBET award #1454166 and support from the Golisano Institute for Sustainability (GIS) at the Rochester Institute of Technology. They also acknowledge feedbacks on the original draft of this paper from Dr Callie Babbit (GIS), Dr Roger Chen (GIS) and Dr Anju Gupta (Department of Chemical Engineering) of Rochester Institute of Technology.

References

Alonso, E., Field, F.R., Kirchain, R.E., 2012. Platinum availability for future automotive technologies. Environ. Sci. Technol. 46 (23), 12986–12993.
Barnhart, J., 1997. Occurrences, uses, and properties of chromium. Regul. Toxicol. Pharmacol. 26 (1), S3–S7.
Bayliss, C., 2019. Aluminum trends. In: Gaustad, G. (Ed.), The Minerals, Metals, and Materials Society. TMS, San Antonio, Texas.
Boon, J.E., Isaacs, J.A., Gupta, S.M., 2000. Economic impact of aluminum-intensive vehicles on the U.S. Automotive recycling infrastructure. J. Ind. Ecol. 4 (2), 117–134.
Brooker, A.D., Ward, J., Wang, L., 2013. Lightweighting Impacts on Fuel Economy, Cost, and Component Losses, SAE 2013 World Congress and Exhibition. SAE International.
Brooks, L., Gaustad, G., Gesing, A., Mortvedt, T., Freire, F., 2019. Ferrous and non-ferrous recycling: challenges and potential technology solutions. Waste Manage. 85, 519–528.
Chappuis, L.B., Material Specification and Recycling for the 2015 Ford F-150. Vehicle Program Engineering - Manufacturing.
Cheah, L., Heywood, J., 2011. Meeting U.S. Passenger vehicle fuel economy standards in 2016 and beyond. Energy Policy 39 (1), 454–466.
Cheah, L.W., 2010. Cars on a Diet: the Material and Energy Impacts of Passenger Vehicle Weight Reduction in the US.
Ciacci, L., Reck, B.K., Nassar, N.T., Graedel, T.E., 2015. Lost by design. Environ. Sci. Technol. 49 (16), 9443–9451.
Cui, J., Roven, H.J., 2010. Recycling of automotive aluminum. Trans. Nonferrous Met. Soc. China 20 (11), 2057–2063.
Department of the Interior, 2018. Final list of critical minerals 2018. Fed. Regist. 83, 23295.
Ducker Worldwide, 2017. Aluminum Content in North American Light Vehicles 2016 to 2028. DriveAluminum.
European Aluminium, Aluminium Automotive Manual.
European Aluminium Association, 2002. Materials - Alloy Constitution. The Aluminum Automotive Manual.
European Commission, 2017. 2017 List of Critical Raw Materials for the EU, Communication From the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. European Commission.
Fridlyander, I.N., Sister, V.G., Grushko, O.E., Berstenev, V.V., Sheveleva, L.M., Ivanova, L.A., 2002. Aluminum alloys: promising materials in the automotive industry. Met. Sci. Heat Treat. 44 (9), 365–370.
Gaustad, G., 2009. Towards sustainable material usage: time-dependent evaluation of upgrading technologies for recycling, materials science and engineering. Massachusetts Institute of Technology.
Gaustad, G., Li, P., Kirchain, R., 2007. Modeling methods for managing raw material compositional uncertainty in alloy production. Resour. Conserv. Recycl. 52 (2), 180–207.
Gaustad, G., Olivetti, E., Kirchain, R., 2010. Design for recycling. J. Ind. Ecol. 14 (2), 286–308.
Graedel, T.E., Allwood, J., Birat, J.P., Buchert, M., Hagelüken, C., Reck Barbara, K., Sibley Scott, F., Sonnemann, G., 2011. What do we know about metal recycling rates? J. Ind. Ecol. 15 (3), 355–366.
Hatayama, H., Tahara, K., 2015. Criticality assessment of metals for Japan's resource strategy. Mater. Trans. 56 (2), 229–235.
Kim, H.-J., McMillan, C., Keoleian, G.A., Skerlos, S.J., 2010. Greenhouse gas emissions payback for lightweighted vehicles using aluminum and high-strength steel. J. Ind. Ecol. 14 (6), 929–946.
Laner, D., Rechberger, H., 2016. Material flow analysis. In: Finkbeiner, M. (Ed.), Special Types of Life Cycle Assessment. Springer Netherlands, Dordrecht, pp. 293–332.
Miller, W.S., Zhuang, L., Bottema, J., Wittebrood, A.J., De Smet, P., Haszler, A., Vieregge, A., 2000. Recent development in aluminium alloys for the automotive industry. Mater. Sci. Eng. A 280 (1), 37–49.
Modaresi, R., Müller, D.B., 2012. The role of automobiles for the future of aluminum recycling. Environ. Sci. Technol. 46 (16), 8587–8594.
Moss, R.L., Tzimas, E., Willis, P., Arendorf, J., Thompson, P., Chapman, A., Morley, N., Sims, E., Bryson, R., Peason, J., 2013. Critical metals in the path towards the decarbonisation of the EU energy sector. Assessing rare metals as supply-chain bottlenecks in low-carbon energy technologies. JRC Report EUR 25994.
Nansai, K., Nakajima, K., Kagawa, S., Kondo, Y., Suh, S., Shigetomi, Y., Oshita, Y., 2014. Global flows of critical metals necessary for low-carbon technologies: the case of neodymium, cobalt, and platinum. Environ. Sci. Technol. 48 (3), 1391–1400.
Nassar, N.T., Graedel, T.E., Harper, E.M., 2015. By-product metals are technologically essential but have problematic supply. Sci. Adv. 1 (3), e1400180.
National Research Council, 2008. Critical Minerals, Minerals, Critical Minerals, and the U.S. Economy. The National Academies Press, Washington, DC.
Nuss, P., Harper, E.M., Nassar, N.T., Reck, B.K., Graedel, T.E., 2014. Criticality of Iron and its principal alloying elements. Environ. Sci. Technol. 48 (7), 4171–4177.
Peiró, L.T., Méndez, G.V., Ayres, R.U., 2013. Material flow analysis of scarce metals: sources, functions, end-uses and aspects for future supply. Environ. Sci. Technol. 47 (6), 2939–2947.
Petit, S., 2018. North America Light Vehicle Production up 1.3% in September. Wards Intelligence.
Restrepo, E., et al., 2017. Stocks, flows, and distribution of critical metals in embedded electronics in passenger vehicles. Environ. Sci. Technol. 51.3, 1129–1139.
Staley, J.T., Lege, D.J., 1993. Advances in aluminium alloy products for structural applications in transportation. J. Phys. IV France 03 (C7) C7-179-C177-190.
Staley, J.T., Van Horn, Kent R., Bridenbaugh, P.R., 2018. Aluminum Processing, Encyclopaedia Britannica. Encyclopaedia Britannica, inc.
U.S. Geological Survey, 2018. Mineral commodity summaries 2018. Department of the Interior (Ed.). U.S. Geological Survey, pp. 200.
US Environmental Protection Agency, 2018. 2018 EPA Automotive Trends Report.
USEPA, 2018a. Inventory of US. Greenhouse Gas Emissions and Sinks: 1990-2016. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2016.
USEPA, 2018b. Sources of Greenhouse Gas Emissions. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions#transportation.
USEPA, 2018c. Trends in Greenhouse Gas Emissions. https://www.epa.gov/sites/production/files/2018-01/documents/2018_chapter_2_trends_in_greenhouse_gas_emissions.pdf.
Wagstaff, S.R., 2018. The Impact of Recycling on the Mechanical Properties of 6XXX Series Aluminum Alloys.
Zimmermann, T., Gößling-Reisemann, S., 2013. Critical materials and dissipative losses: a screening study. Sci. Total Environ. 461 (Supplement C), 774–780.