Recyclability Index for Automobiles

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ABSTRACT

A rating system was developed to quantify the environmental impacts of light-duty motor vehicles at the end of their life-cycle based on recyclability, toxic material content and ultimate disposal. Each year, 10-11 million vehicles are retired from service in the United States. The vehicle material not recycled is called automotive shredder residue (ASR). About 4.5 to 5 million tons of ASR are disposed in U.S. solid waste landfills annually. The volume of this residue is likely to increase as vehicle manufacturers continue to use more plastics and composites in their designs to reduce weight and increase fuel efficiency. The rating system developed here will help educate consumers about environmental performance and allow them to factor this performance into their choice of automobiles. The score of this rating system has the potential to appear on new vehicle stickers, similar to the fuel efficiency value. This, in turn, is expected to influence the vehicle manufacturers' choices of design and manufacturing methods. This would provide a voluntary incentive for pollution prevention in much the same way as the Toxic Release Inventory helps reduce the amount of hazardous waste produced. The end-of-life vehicle (ELV) rating system, modeled after life cycle assessment, has two parts: one based on recyclability and one based on toxicity. The recyclability portion is based on the content of ferrous and non-ferrous metal content (which is 100% recyclable) and plastic for which there is a market for recycling. The toxicity index is based on the content of lead (excluding batteries, which are recycled), mercury, cadmium and chromium. This rating system was tested on a generic 1995 vehicle. The paper also includes an analysis of the aggressive ELV legislation approaches of Europe and Japan.

INTRODUCTION

The world population depends on automobiles with about 700 million cars, trucks and other vehicles currently in use worldwide (EPA, 2004). Each year in the United States, 10-11 million vehicles are retired from service because of major component failure, structural integrity loss due to extended normal wear, corrosion or accidents (Environmental Defense, 1999). Currently, about 75% of the vehicle mass is recycled in the United States (Bandivadekar, 2004). The remaining non-recoverable material is called Automotive Shredder Residue (ASR) and mainly consists of the non-metallic materials (e.g. plastics, glass, carpeting). 4.5 to 5 million tons of ASR are generated each year in the United States and land-filled across the country (Keoleian, 2001). The resource-consumption and waste-management problems created by ASR is likely to grow as vehicle manufactures continue to use more plastics, fibers, and composites to reduce weight and increase fuel efficiency (Environmental Defense, 1999). Plastics are the fastest growing component of waste at the automobile’s end-of-life (Griffith, 2005).

Currently, plastics make up about 9% of the vehicle weight. This percentage is up from 0.6% of the vehicle weight in 1960. By 2020, the automotive plastics industry wants to establish plastics as the material of choice in many automotive components and systems design because of the lightweight nature of plastics (Foster, 2004).

In addition to designing for light weight and fuel efficiency, it is also important to improve automobile design to reduce the volume and weight of ASR. Another problem with ASR is that it is considered a hazardous waste in the state of California if there are significant amounts of toxic contaminants (Barclay, 2006) making it more difficult and expensive to dispose. This paper will describe a rating system quantifying the ecological impacts of end-of-life vehicles ELVs by taking into account recyclability, toxic material content, and disposal. The rating system is designed to educate consumers about the end-of-life impact of cars they are planning to purchase. Currently, consumers can see information such as the fuel efficiency on the new vehicle sticker. Similarly, the score from this rating system can be placed on this sticker. The system will help to close the recycling loop when the consumer purchases vehicles made with recoverable materials. Though manufacturers are in the best position to address these environmental impacts, consumers can cause producers to change their choice of materials (Environmental Defense, 1999).

BACKGROUND

Steps in typical processing an End-of-Life Vehicle (ELV) are shown in the flow diagram in Figure 1. First, the ELV is dismantled at a high-value parts dismantler or salvage yard. High-value parts removed for resale are listed in Table 1. After the vehicle is dismantled, the remaining hulks (consisting of steel structural material, plastic dashboard, foam seats and other components) is flattened, and shipped to a shredding facility.

Figure 1: ELV Recycling and Disposal Process Flow Diagram (Keoleian, 2001)

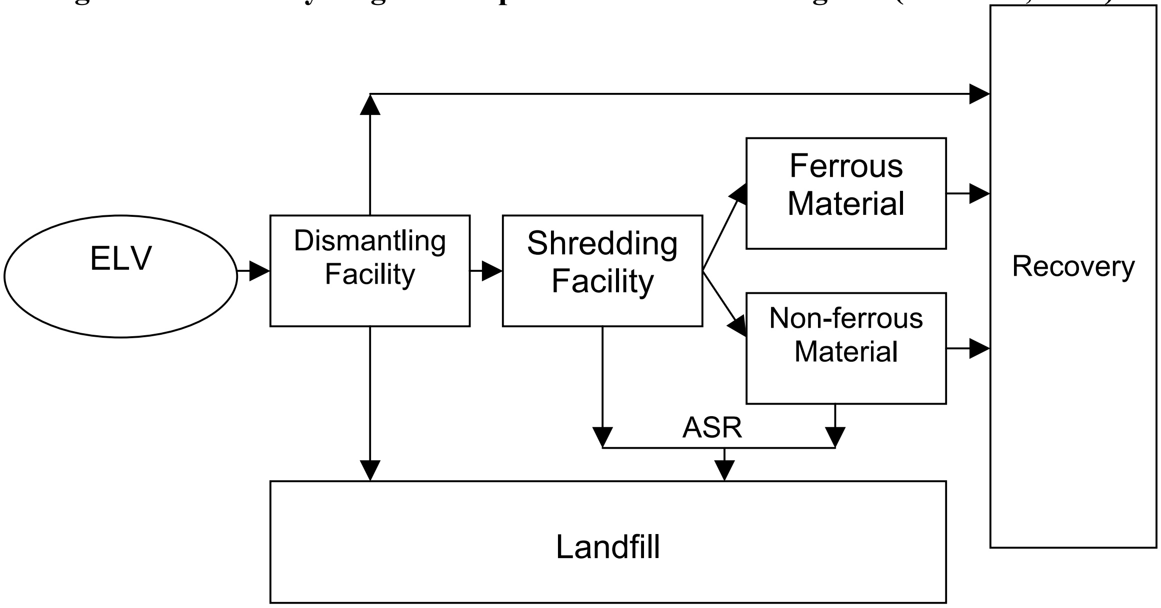


Table 1. ELV Parts and Use (Keoleian, 2001)

Type	Use
clutch, water pump, engine, starter, alternator, transmission	remanufacture and sell for reuse
wheels, body panels	repair accident damaged vehicles
aluminum/copper parts	sold to nonferrous processors
gasoline	recover for use
antifreeze, windshield cleaning fluid	recycle
air conditioning and refrigerant gases	recover for use or destruction
lead acid battery	recycle
tires	burn for energy recover, landfill, or stockpile
catalytic converters	recover for precious metal
air bags	reuse/dispose
fuel tanks	recycle steel landfill plastic

The hulk becomes fist-sized pieces consisting of the components in Table 2. The ferrous material (steel and iron) is magnetically separated from the non-ferrous material (metal and non-metal) and is sent to a steel smelter that specializes in processing steel scrap. The non-ferrous material will be sent to a separation facility that recovers the non-ferrous metal (brass, bronze, copper, lead, magnesium, nickel, and stainless steel). What remains in the ASR, The typical make up of which is shown in Table 3. This is sent to landfills for disposal (Keoleian, 2001).

Table 2. Shredded Material Components (Keoleian, 2001)

Type	**Examples**	**Percent weight**
ferrous metals	iron, steel	65 to 70
non-ferrous metals	aluminum, stainless steel, copper, brass, lead, magnesium, zinc, nickel	5 to 10
ASR	plastic, glass, rubber, foam, carpet, textile	20 to 25

Table 3. ASR Components (Keoleian, 2001)

Type	**Percent**
Plastic	31
Rubber	8
Glass	12
Other material (carpet, textiles)	13
Dirt, metal fines	20
moisture	15

Global legislation

Europe and Japan have addressed the impacts of ELVs in recent aggressive legislation (Europa, 2005) (Togawa, 2005). Similar to this project, the legislation has focused on the use of toxic materials in the automobile and the recyclability of the automobile. The European Union passed a directive mandating recycling goals of 85% vehicle recycling rates by 2006 and 95% vehicle recycling rates by 2015. The objectives of the legislation also ban hazardous material use such as mercury, hexavalent chromium, cadmium, and lead. Since the producer is held responsible for recycling costs, the last holder of the ELV can dispose of the vehicle free of charge. Member states will need to set up ELV collection systems and implement material coding for proper identification of the materials during dismantling. Every three years, the member states will report to the commission on the implementation of the directive (Europa, 2005).

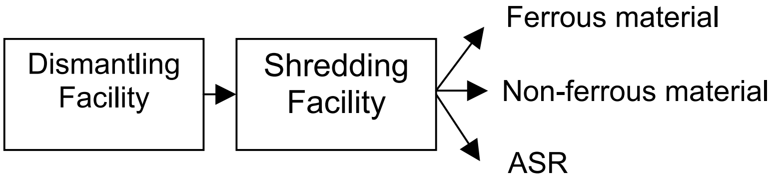
Japanese automakers were compelled to make a response to this for two reasons: the European Union is an important market for Japanese automakers, and the ELV directive has implications of a global standard. In the beginning of 2005, the Japan Automobile Recycling Law came into effect focusing on CFC, airbag and ASR disposal (Togawa, 2005). The goals of the legislation slightly differ from the EU legislation by focusing on the recycling rates of ASR rather than the total vehicle. However, the percent weight recycled of the automobile recycled is the same in the Japanese and EU legislation. The Japanese legislation calls for, by the end of 2005, the ASR recycling rate to be at 30%, corresponding to a vehicle recycling rate of 88%. By 2010, the ASR recycling rate will increase to 50% (vehicle recycling rate of 92%), and finally in 2015, the ASR recycling rate is mandated at 70% (vehicle recycling rate of 95%) (Toyota, 2006). In contrast to the EU legislation, customers in Japan will bear the recycling costs by paying a deposit recycling fee when purchasing a new car, or when their car is inspected or deregistered.

The manufacturer will be responsible for removing and recycling the CFCs, airbags, and ASR (Togawa, 2005). The Japan Automobile Manufacturers Association will be responsible for enforcing the law (Isuzu, 2004). This law does not ban any hazardous material use; however, there is a voluntary initiative restricting the use of hazardous materials (Togawa, 2005). These legislations created goals for making the automotive industry more conscious to the environment. Instead of relying on regulation, we set out to design a tool which would allow market forces to implement similar improvements in the United States.

Automobile Recycling Process

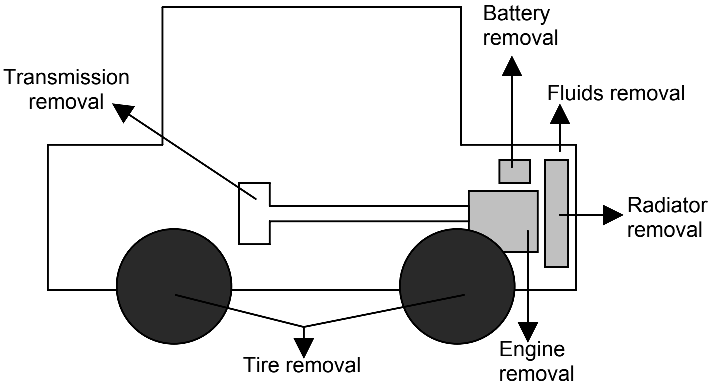
This rating system is based on the recycling process shown below in Figure 2.

Figure 2: Recycling Process Chosen for Rating System



At the dismantling facility, the components are removed from the vehicle as depicted in Figure 3.

Figure 3: Components Removed from Vehicle



The following fluids are removed from the vehicle: fuel, motor oil, transmission oil, brake fluid, antifreeze, and freon. After these components are removed, the car is crushed at the dismantling facility and taken to the shredding facility.

The recycling process must be defined to understand which components will contribute to the recyclability and toxicity rating. For example, since the lead battery is removed during the recycling process, this lead amount is not considered in the toxicity rating. This process was determined by examining current California law (Arcaute, 2004), and recommendations of the State of California Auto Dismantler's Association (State of California, 1999). Though this process is chosen as a basis for the rating system, due to higher demands on certified recyclers, there are a growing number of unlicensed dismantlers not adhering to environmental regulations (Arbitman, 2003). Due to these factors, the accuracy of this rating system is dependent on the effective regulation of auto dismantlers.

RATING SYSTEM

This rating system is based on the materials used in a particular automobile model and will output two values: a recyclability score and a toxicity score. The recyclability score will reflect this amount of the automobile that can be typically recycled and diverted from the landfill. The toxicity score will reflect the potential human health effects of the hazardous materials in the ASR.

Recyclability Score

For the first part of the system, the recyclability score (R) will be based on the ISO 22628 standard for calculating automobile recyclability (The International Organization for Standardization, 2002). The equation is shown as the following:

Equation 1.

$$R = \frac{m_m + m_{rp}}{m_v} * 100$$

where:

m_m = the weight of metal in a vehicle and is found with the following equation:

Equation 2.

$$m_m = m_f + m_{nf}$$

where:

m_f = the ferrous metal mass,

m_{nf} = the non-ferrous metal mass

m_{rp} = the weight of recyclable plastic in a vehicle,

m_v = the total weight of the vehicle

The weight of the recyclable plastic in a vehicle(m_{rp}) is determined by the following equation:

Equation 3.

$$m_{rp} = r_{p,1} * m_{p,1} + r_{p,2} * m_{p,2} + r_{p,3} * m_{p,3} ... + r_{p,n} * m_{p,n}$$

where:

$r_{p,1}$ = the recycled market ability of plastic 1. If a plastic has a recycled market value, then the *r* value will be 1. If the plastic does not have a recycled market value, the *r* value will be 0,

$m_{p,1}$ = the mass of plastic 1.

Using Equation 3, the mass of all the ELV plastics with actual value are summed together. If the plastic is theoretically recyclable, but does not have a market, this system will assume that it is land-filled. This is a valid assumption because the recycling industry is market driven, so if there is no market value for a material, it will not be recycled.

With this analysis, the only plastics currently considered to have a market value in 2006 are high density polyethylene (PE) and polyethylene terephthalate (PET) (American Metal Market 2006). Therefore, the equation can be simplified to the following:

$$m_{rp} = r_{p,1} * m_{p,1} + r_{p,2} * m_{p,2}$$
$$m_{rp} = r_{pe} * m_{pe} + r_{pet} * m_{pet}$$

where:

r_{pe} = 1 for polyethylene plastic (PE),

m_{pe} = the mass of PE,

r_{pet} = 1 for polyethylene terephthalate plastic (PET),

m_{pet} = the mass of PET

The final equation for m_{rp} is thus:

Equation 4.

$$m_{rp} = m_{pe} + m_{pet}$$

Therefore, with all the substitutions, the recyclability score based on the 2006 market for recycled plastic is calculated by the following equation:

$$R = \frac{(m_f + m_{nfp}) + (m_{pe} + m_{pet})}{m_v} * 100$$

Toxicity Score

The next part of the rating system looks at the automobile's toxic materials. The selected toxic materials for analysis are shown in Table 4 with their corresponding use in automobiles and their potential health impacts.

Table 4: Summary of the Toxic Materials in an Automobile: Applications and Health Impacts

	Automobile Application	**Health Impacts**
Lead	batteries, wheel balance weights, alloys	brain and kidney damage (Gearhart, 2003)
Mercury	switches, lamps	brain and nervous system damage (Wisconsin, 2005)
Cadmium	surface coating	kidney disease (EPA, 2000)
Hexavalent Chromium	surface coating	lung cancer (US OSHA, 2000)

Substances of Concern

The four heavy metals were chosen because they are the substances of concern pertaining to automobiles in Europe and Japan. The European Union passed a directive banning the use of these hazardous materials in automobiles (Europa, 2005). Also, in Japan, there is a voluntary initiative restricting the use of these hazardous materials (Togawa, 2005). The average amounts found in an automobile are shown in Table 5.

Table 5: Typical Quantities of Heavy Metals in an Automobile

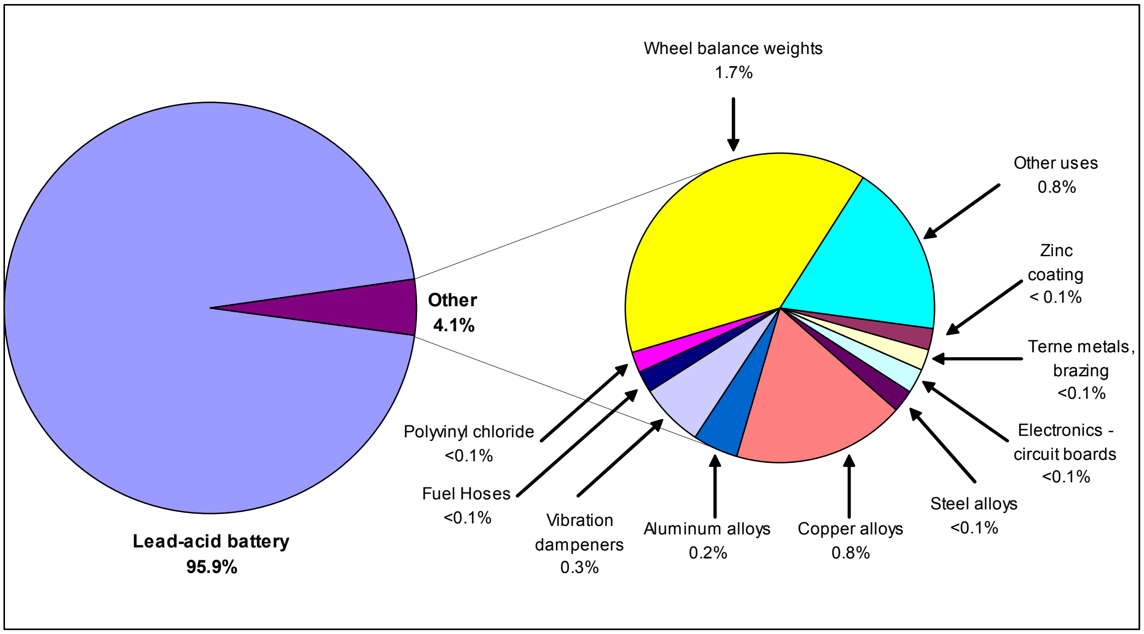
	Weight (grams)	**Source**
Lead	500	(Gearhart, 2003)
Hexavalent Chromium	16.5	(Preikschat, 2003)
Mercury	0.9	(Davis, 2001)

Lead

Lead is a toxin with many health impacts. In children, lead can cause brain damage and kidney damage, while in adults, lead can cause kidney damage and nerve disorders (Gearhart, 2003).

Each car manufactured today contains about 27 pounds of lead used in vehicle components (Gearhart, 2003). Figure 4 shows the lead content of automobiles.

Figure 4: Lead Content of Automobiles (Gearhart, 2003)



The battery contains the most lead in the automobile and batteries are effectively recycled (about 90% of all lead acid-batteries are recycled (EPA, 2006)), thus not part of this ELV rating. However, the environmental contamination from the remaining quantities of lead (4.1% - see Figure 4) is still significant. Lead in steel alloys and automotive coatings are released to the environment when metals are recycled. When the automobile is shredded, lead contaminates the entire shredded product (ferrous, non-ferrous and ASR portions) and contributes to lead emissions to the environment. Table 6 below shows a significant amount of lead in ASR.

Table 6: Lead Content of ASR (Gearhart 2003)

Data source	**Lead concentration (mg/kg)**	**Lead in ASR, Average (metric tons per year)[a]**	
		U.S.	**Canada**
Umweltsbundesamt, Germany (Weiss, 1996)	3,500-7,050	15,825	1,583
Environmental Protection Agency, USA (EPA, 1991)	570-12,000	18,855	1,886
Department of Health Services, California (Nieto, 1989)	2,330-4,616	10,419	1,042
Average	--	15,033	1,504
a. Based on 3 million metric tons of ASR potentially landfilled each year in the U.S. and 300,000 metric tons in Canada			

Lead was thus considered one of the metals of concern in ASR causing the California Department of Health Services to designate ASR as hazardous waste (EPA, 1991). ASR is considered hazardous waste when the lead concentration is over 50 mg/l (Barclay, 2006). When the scrap metal from automobiles is processed by steel smelters, the impurities are removed as slag or released as dust and gaseous by-products to the environment. The generated slag and dust are also listed as hazardous waste.

Hexavalent Chromium

Hexavalent chromium causes lung cancer and can cause skin ulcers under prolonged skin contact (US OSHA, 2000). Chromium is used as a coating for automobile parts due to the characteristics of appearance, durability, and corrosion resistance (Graves, 2000). The most commonly used method of chrome plating is the traditional coating system using electroplated zinc followed by hexavalent chromium (Wynn, 2003).

Cadmium

Cadmium is very toxic to humans because it can accumulate in the kidneys and cause kidney diseases (EPA, 2000). Cadmium is used in the automobile industry as a fastener coating (IHS Inc., 2004). Cadmium has many favorable features for the automotive industry such as excellent anti-corrosion properties, lubricity, and good solderability (Wilson, 1986).

Mercury

Mercury can cause both brain and nervous system damage. It also accumulates up the food chain leading to higher concentrations in top level predators (Wisconsin, 2005). The California Department of Health Services concluded that mercury is another one of the metals of concern to classify ASR as hazardous waste (Posselt, 2000). ASR is considered hazardous waste when it has over 0.2 mg/l of mercury (Barclay, 2006). Mercury switches are used in convenience lighting, anti-lock braking system systems (ABS), active ride controls systems, high intensity discharge headlamps, and fluorescent lamps (background lighting, speedometers) (Gearhart, 2004). These mercury switches account for more than 99% of the mercury used in automobiles, with each switch containing approximately 0.8 grams of mercury (Davis, 2001). Though the use of mercury in convenience lighting switches has declined about 70% since 1996, the use in other applications (ABS, high intensity discharge headlamps, navigation displays, family entertainment systems) is rising. For ABS applications, it has risen about 160% since 1996. Little known recovery of mercury switches during automobile dismantling or recycling is practiced (Davis, 2001).

Most of the mercury in ELVs is released to the environment when the steel smelters process the recycled scrap metal. These smelters are the single largest manufacturing source of mercury air emissions (15.6 metric tons/year) in the US – larger than all other manufacturing sources combined. It is the 4th largest of all mercury air emission sources, behind coal-fired utilities, municipal waste incinerators, and commercial/industrial boilers (Davis, 2001).

The ELVs created in the United States last year contained a total of nine metric tons of mercury (Keoleian, 2001). Over the last 30 years, 120 metric tons of mercury has been released into the environment due to vehicle disposal. An equal amount could be released over the next two decades if mercury use is not abated or if action to recover the mercury is not taken (Gearhart, 2004).

Toxicity Rating System

The toxicity score is determined by using the scoring developed by Hertwich and Pease (Scorecard, 2005). The system uses the Toxic Equivalency Potential (TEP) as a weighting factor comparing chemical releases on a common scale taking into account differences of toxicity and exposure potential. The TEP indicates the human health risk (cancerous and non-cancerous) related with the release of one pound of chemical (into the air or water) compared to the risk of a reference material (Scorecard, 2005).

The TEP is calculated using the CalTOX model. The CalTOX system is an environmental fate and exposure model used by California regulatory agencies(Scorecard, 2005). This system has also been evaluated by the EPA's Science Advisory Board of Integrated Human Exposure Committee. The system uses the physical-chemical properties and landscape characteristics of the environment (how the chemical is distributed into the environment) (Scorecard, 2005). The CalTOX risk scores for the hazardous materials considered in this study are shown below in Table 7.

Table 7: Risk scores for hazardous materials

	Cancer risk score for air release (per pound of heavy metal)	Cancer risk score for water release (per pound of heavy metal)	Noncancer risk score for air release (per pound of heavy metal)	Noncancer risk score for water release (per pound of heavy metal)
Cadmium	26,000	1,900	1,900,000	140,000
Chromium	130	0	2,400	260
Lead	28	2	580,000	42,000
Mercury	0	0	14,000,000	13,000,000

Each of these risk scores are multiplied by the mass of the hazardous material found in the automobile to determine the corresponding TEP score. Each hazardous material will have a four TEP values: Cancer TEP (air release), cancer TEP (water release), noncancer TEP (air release) and noncancer TEP (water release). The cancer TEP scores will are expressed in terms of pounds of benzene-equivalents, while the noncancer TEP scores are expressed in terms of pounds of toluene-equivalents (Scorecard, 2005). The total TEP score of the automobile consists of the total cancer TEP score and total noncancer TEP score. The total cancer TEP score will be determined by adding up all the cancer TEP scores and, similarly, the non-cancer TEP score will be determined by adding up all the noncancer TEP scores. Table 8 and 9 below show how the information can be organized.

Table 8: Cancer TEP Scores Organization Chart

	Cancer TEP (air release)	Cancer TEP (water release)	Total Cancer TEP
Cadmium			
Chromium			
Lead			
Mercury			
Automobile cancer TEP score:			

Table 9: Noncancer TEP Scores Organization Chart

	Noncancer TEP (air release)	Noncancer TEP (water release)	Total noncancer TEP
Cadmium			
Chromium			
Lead			
Mercury			
Automobile noncancer TEP score:			

Case Study

This case study was done with the following data set shown in Table 10 based on a generic US sedan as described by Sullivan (1998).

For this typical car, the recyclability score(R) is:

$$R = \frac{m_m + m_{rp}}{m_v} * 100$$

where:

$$m_m = m_f + m_{nf} = 985kg + 138kg = 1123kg\,,$$

$$m_{rp} = m_{pe} + m_{pet} = 6.2kg + 2.2kg = 8.4kg\,,$$

$$m_v = 1532kg$$

$$R = \frac{1123kg + 8.4kg}{1532kg} * 100 = 73.6\%$$

In order to determine the TEP score for the automobile, the masses of the four hazardous materials were used as shown in Table 11.

Table 10: 1995 Model Year Generic US Family Sedan (Sullivan 1998)

Material Category/ Material	mass (kg)	Material Category/ Material	mass (kg)
Plastics		**Ferrous Metals**	
ABS	9.7	iron (ferrite)	1.5
ABS-PC blend	2.8	iron (cast)	132
Acetal	4.7	iron (pig)	23
Acrylic Resin	2.5	steel (cold rolled)	114
ASA	0.18	steel (EAF)	214
Epoxy Resin	0.77	steel (galvanized)	357
PA 6	1.7	steel (hot rolled)	126
PA 66	10	steel (stainless)	19
PA 6-PC blend	0.45	**Subtotal**	**985**
PBT	0.37	**Fluids**	
PC	3.8	auto trans.fluid	6.7
PE	6.2	engine oil	3.5
PET	2.2	ethylene glycol	4.3
Phenolic Resin	1.1	gasoline	48
Polyester Resin	11	glycol ether	1.1
PP	25	refrigerant	0.91
PP foam	1.7	water	9
PP-EPDM blend	0.1	windshield cleaning additives	0.48
PPO-PC blend	0.025		
PPO-PS blend	2.2	**Subtotal**	**74**
PS	0.007	**Other Materials**	
PUR	35	adhesive	0.17
PVC	20	asbestos	0.4
Thermoplastic Elastomeric Olefin (TEO)	0.31	bromine	0.23
Subtotal	**143**	carpeting	11
Non-Ferrous Metals		ceramic	0.25
aluminum oxide	0.27	charcoal	0.22
aluminum (cast)	71	corderite	1.2
aluminum (extruded)	22	desiccant	0.023
aluminum (rolled)	3.3	fiberglass	3.8
brass	8.5	glass	42
chromium	0.91	graphite	0.092
copper	18	paper	0.2
lead	13	rubber (EPDM)	10
platinum	0.002	rubber (extruded)	37
rhodium	0.0003	rubber (tires)	45
silver	0.003	rubber (other)	23
tin	0.067	sulfuric acie - in bat	2.2
tungsten	0.011	textile fibers	12
zinc	0.32	wood	2.3
Subtotal	**138**	**Subtotal**	**192**
		Grand Total	**1532**

Table 11: Masses of Hazardous Materials

	Weight (kilograms)	Weight (pounds)
cadmium	n/a	n/a
chromium	0.91	2
lead	0.533	1.18
mercury	0.009	0.02

These masses were multiplied by the corresponding risk scores in order to find the TEP scores as shown in Table 12 below. Though the lead amount in Table 10 lists 13 kilograms, it is assumed that 95.9% of this weight is due to the battery (See Figure 4). The remaining 4.1% or 0.533 kilograms will be used in for the toxicity score rating. Since there was no weight of mercury listed in Table 10, the typical value of mercury from Table 5 was used in this case study.

Table 12: Cancer TEP score (in pounds of benzene) for the Case Study

	Cancer TEP (air release)	Cancer TEP (water release)	Total Cancer TEP
Cadmium	n/a	n/a	n/a
Chromium	260	0	260
Lead	33	2	35
Mercury	0	0	0
Automobile cancer TEP score:			**295**

Table 13: Noncancer TEP score (in pounds of toluene) for the Case Study

	Noncancer TEP (air release)	Noncancer TEP (water release)	Total noncancer TEP
Cadmium	n/a	n/a	n/a
Chromium	4,800	520	5,320
Lead	448,400	49,560	497,960
Mercury	280,000	260,000	540,000
Automobile noncancer TEP score:			**1,043,280**

The final ratings of this automobile are shown in Table 14 below.

Table 14: 1995 Generic US Family Sedan Rating

Recyclability Score		73.6%
Toxicity Score	Cancer TEP	300 pounds of benzene
	Noncancer TEP	0.5 tons of toluene

In order to implement this rating system, comprehensive material listings are needed from manufacturers. Unfortunately, such information is often proprietary and not in the public domain. In order to obtain such information for running examples for this study, various industry professionals have been contacted at automobile manufacturers such as GM, Ford, Daimler Chrysler, Toyota, Honda, Nissan, BMW, Hyundai, Fiat, Isuzu, Mazda, Mitsubishi, Porsche, Suzuki, Volkswagen, and Volvo. Also, to locate references and obtain more industry information, trade associations dealing with ELVs have been contacted. These trade associations include Automotive Recyclers Association, State of California Auto Dismantler's Association, Japan Automotive Recyclers Association, Automotive Recyclers of Canada, European Group of Automotive Recycling Association, Institute of Scrap Recyclers Industries, and the Steel Recycling Institute. Though contact was made the authors were unable to obtain comprehensive material listings through any of these channels except at Honda Corporation.

Comparison to the European System

In Europe, in order to measure recyclability, the ISO 22628 standard is used. The rating system described in this paper uses this standard as a basis. There are two measurements calculated in the ISO method: recyclability and recoverability(The International Organization for Standardization, 2002). The difference between these two measurements is that the recyclability includes the mass of the automobile that can be incinerated for energy recovery, where recoverability does not(The International Organization for Standardization, 2002). Since ASR is not incinerated in the US(Keoleian, 2001), the recycability score described in this paper is more closely related to the ISO 22628 recoverability measurement. There are a few differences between the ISO 22628 standard and the recyclability score described in this paper. The ISO standard includes other masses such as the mass of components or materials removed during the pre-treatment step. These items include fluids, oil filters, gas tanks and tires. The ISO standard also includes the mass of salvageable (reusable) and recyclable components. Salvageable components are determined by their accessibility, fastener technologies, material composition and proven recycling technology(The International Organization for Standardization, 2002). The rating system described here does not include these two mass terms because the system is designed to only use a material listing, not a corresponding component listing. Finally, the ISO standard includes the mass of non-metallic residue. This similar to the weight of recyclable plastics (m_{rp}) described in this paper. The ISO non-metallic residue mass is based on proven recycling technologies and can include the mass of many materials such as glass and rubber(The International Organization for Standardization, 2002). The m_{rp}, described in this paper, only includes the mass of plastic and is based on the recycling market for this plastic.

For hazardous materials, Europe has banned the use of mercury, hexavalent chromium, cadmium, and lead. There are exemptions to these restrictions as shown in Table 15.

Table 15: Hazardous Material Use Exemptions in Europe (Beckett, 2005)

Hazardous Material	Application Exemption
Lead	alloys
	batteries
	vibration dampeners
	stabilizers in elastomers
	solder in electric applications
Hexavalent Chromium	corrosion preventive coatings
Mercury	discharge lamps
	instrument panel displays
Cadmium	thick film pastes
	batteries for electric vehicles

This rating system described in this paper only exempts the lead used in the battery because lead batteries are highly recycled(EPA 2006). Also, if the lead battery amount was not taken out of this rating system, the toxicity score would be significantly higher and inaccurate. The other European exemptions are not included in this rating system. This system will equally penalize all manufacturers for the use of the hazardous materials and will encourage manufacturers to find material substitutions.

CONCLUSIONS

A tool to rate the end-of-life impacts of automobiles has been successfully developed. If implemented, this analysis tool could educate consumers on the impacts of the new vehicle they are planning to purchase. Implementation would require cooperation of manufacturers, possibly mandated by the US EPA. More manufacturer cooperation in providing material data sheets would have significantly helped this study. By understanding the impacts, consumers will be able to make conscious decisions about the vehicles they demand and hopefully stimulate market forces to help protect the environment. The rating system focuses on the material content of automobiles and the impacts associated with these materials. In order to strengthen this rating system, different aspects of the automobile need to be viewed such as manufacturing design. Also, this rating system could have been strengthened by including the analysis of materials in relation to their component weights. However, even if this analysis was done, the study would have been affected by the same obstacle of unattainable manufacturer data. Recycling yard practice is also very important to this rating system because the rating generated from this system will not reflect accurate end-of-life impacts if improper recycling practices occur.

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REFERENCES

American Metal Market. February 24, 2006 Recyclable Material Prices [article on the Internet].[rev. 2006; cited 2006 8 March]. Available from: http://www.amm.com/recman/price.asp?f=reclos

Arbitman, Nathan; Gerel, Mike. Managing end-of-life vehicles to minimize environmental harm. 2003 Dec. Sustainable Conservation. San Francisco, CA

Arcaute, Francisco. US EPA announces compliance efforts among California auto dismantlers [article on the Internet].[rev 2004 15 April; cited 2006 8 Jan]. USEPA, Region 9: News Release. Available from: http://yosemite.epa.gov/opa/admpress.nsf/0/74a91726bfa5ac99852570d8005e1630?OpenDocument

Bandivadekar, Anup; Kumar, Vishesh; Gunter, Kenneth; Sutherland, John. A model for material flows and economic exchanges within the U.S. automotive life cycle chain. Journal of Manufacturing Systems. 2004. 23 (1). p 22-29.

Barclay’s Official California Code of Regulations. 2006. Treatment standards expressed as concentrations in waste extract. Cal. Admin code Tit. 22, s 66268.106.

Beckett, M. 2005. Council Decision of 20 September 2005 amending Annex II of Directive 2000/53/EC of the European Parliament and of the Council on end-of-life vehicles. Official Journal of the European Union, p. 69-72

Davis, Gary; Dhingra, Rajive; Gearhart, Jeff; Gingras, Stephane; Griffith, Charles; Kincaid, Lori; McPherson, Alexandra; Posselt, Hans. Toxics in vehicles: Mercury implications for recycling and disposal [report on the Internet].[rev 2001 Jan; cited 2005 Jan 12]. University of Tennessee, Center for Clean Products and Clean Technologies. Available from: http://www.p2pays.org/ref/19/18304.pdf

Environmental Defense, Green Cars, End-of-Life Vehicle Management [article on the Internet].[rev 1999; cited 2005 Jan 10]. Available from: http://www.environmentaldefense.org/documents/891_GC%5Feol%2Ehtm

EPA. PCB, lead and cadmium levels in shredder waste materials: A pilot study; EPA 560/5-90-00BA. April 1991.

EPA, Cadmium Compounds, Technology Transfer Network Air Toxics Website [article on the Internet].[rev 2000 Jan; cited 2006 8 Jan]. Available from: http://www.epa.gov/ttn/atw/hlthef/cadmium.html

EPA, Sustainability, Basic Information [article on the Internet].[rev 2004 July 7; cited 2005 Jan 11]. Available from: http://www.epa.gov/sustainability/basicinfo.htm

EPA, Batteries [article on the Internet].[rev 2006 March 1; cited 2006]. Available from: http://www.epa.gov/garbage/battery.htm

Europa. Management of end-of-life vehicles. [article on the Internet].[rev 2005 6 Jan; cited 2006 8 Jan]. Available from: http://europa.eu.int/scadplus/leg/en/lvb/l21225.htm

Foster, Catherine. Argonne, industry to tackle end-of-life vehicle recycling [article on the Internet].[rev 2004 June 14; cited 2005 Jan 9]. Argonne National Laboratory, Energy Systems Division, Vehicle Recycling. Available from: http://www.es.anl.gov/Energy_Systems/Process_Engineering/What%27s_New/What%27s%20New.htm

Gearhart, Jeff; Thomas, Karen. Mercury pollution from automobiles at record levels [article on the Internet].[rev 2004 April 7; cited 2005 Jan 8]. Washington DC: Ecology Center, Clean Car Campaign. Available from: http://www.clearcarcampaign.org/releases/20040407mercury.shtml

Gearhart, Jeff; Griffith, Charles; Menke, Dean; Mills, Kevin. Getting the lead out: Impacts of and alternatives for automotive lead uses. Washington DC: Environmental Defense; 2003.

Graves, Beverly. Alternatives to hexavalent chromium and chromium plating. [article on the Internet].[rev 2000; cited 2006 8 Jan]. Automotive Finishing. Available from: http://www.findarticles.com/p/articles/mi_m0HRR/is_2000_Winter/ai_75577967

Griffith, Charles; Rossi, Mark. Moving Towards Sustainable Plastics: A report card on the six leading automakers. 2005 Feb. Ecology Center. Ann Arbor, MI

IHS Inc. The challenges of fastener finishing [article on the Internet].[rev. 2004 Aug; cited 2006 8 Jan]. Available from: http://auto.ihs.com/newsletters/auto-aug04-fastener-finishing.jsp

Isuzu. Environmental Report 2004. Isuzu Motors Limited. Tokyo, Japan. p. 22.

Keoleian, Gregory; Staudinger, Jeff. Management of End-of-Life Vehicles (ELVs) in the US [report on the Internet]. [rev 2001 March; cited 2005 Jan 12]. University of Michigan, Center for Sustainable Systems. Available from: http://css.snre.umich.edu/css_doc/CSS01-01.pdf

Nieto, Eduardo. Treatment levels for auto shredder waste, State of California Department of Health Services, June 1989.

Posselt, Hans. Comments on the EU green paper “Environmental issues of PVC”. [Document on the Internet].[rev 2000 Nov 30; cited 2005 Jan 15]. Ann Arbor, Michigan: Ecology Center. Available from: http://www.cleancarcampaign.org/pdfs/ec_eupvc_00.pdf

Preikschat, Patricia. EC End of Life Vehicles Directive and Hexavalent Chromium [presentation on the Internet].[rev 2003 Oct; cited 2006 10 Feb]. Available from: www.surtec.com/presentations/arnoldE.pdf

State of California Auto Dismantler's Association. Partners in the solution compliance program standards [article on the Internet].[rev 1999; cited 2006 8 Jan]. Available from: http://www.scada1.com/partners.htm

Sullivan, J.; Williams, R.; Yester, S.; Cobas-Flores, E.; Chubbs, S.; Hentges, S.; Pomper, S. Life cycle inventory of a generic US. family sedan overview of results USCAR AMP project. 1998 Total Life Cycle Conference Proceedings.1998; pp 1-14.

The International Organization for Standardization. 2002. ISO 22628:2002(E) Road vehicles – Recyclability and recoverability – Calculation method.

Togawa, K. 2005. Background of the automobile recycling law enactment in Japan. Environmental Economics and Policy Studies, 6: p. 271-283.

Toyota. Preparing for the Automobile Recycling Law. [article on the Internet].[rev 2006; cited 2006 8 Jan]. Environmental Technology, Recycle. Available from: http://www.toyota.co.jp/en/environment/recycle/law/air_bag.html

US OSHA. Hexavalent chromium: Hazard recognition [article on the Internet].[rev 2000; cited 2006 8 Jan]. Available from: http://www.osha.gov/SLTC/hexavalentchromium/recognition.html

Weiss D, Karcher A (1996) Ermittlung und Verminderung der Emissionen von Dioxinen und Furanen aus thermischen Prozessen: Untersuchung der Zusammenhaenge der Dioxin-/Furanemissionen in Abhaengigkeit von Einsatzstoffen und Minderungstechniken bei Elektro-Lichtboegenoefen, Forschungsbericht 104 03 365/17, Umweltbundesamt[UBA].

Wilson, D. Markets for cadmium plated products. 1986. Cadmium Today. Brussels, Belgium. 42-45.

Wisconsin Department of Natural Resources. Mercury Switch Recycling Program [article on the Internet].[rev. 2005 14 Nov; cited 2006 8 Jan]. Available from: http://www.dnr.state.wi.us/org/caer/cea/assistance/scrap/switches/

Wynn, Paul. The end of life vehicle directive and international material data system [article on the Internet].[rev 2003; cited 2006 8 Jan]. Available from: http://www.pfonline.com/articles/050304.html

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