Sustainability Issues Affecting the Successful Management and Recycling of End-of-Life Vehicles in Canada and the United States

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Abstract As the manufacturing and operation of vehicles become increasingly efficient, the environmental impacts of vehicles at the end-of-life phase become more significant. However, the effective recovery of recyclable parts and materials (particularly plastics) from end-of-life vehicles (ELVs) is fraught with challenges. For example, limited market demand for particular part and material types, dismantling difficulties (e.g., rusted part fasteners; welded parts assemblages), and non-uniformity of legislated controls and/or restrictions will influence the successful recovery and recycling of dismantled parts and materials. Automotive material variety and complexity combined with the limited effectiveness of processing technologies for liberating and separating automotive materials (plastics in particular) into sufficiently pure and recyclable material streams tend to limit materials recovery and recycling to principally automotive ferrous and non-ferrous metals. This chapter presents an overview and conceptual analysis of vehicle end-of-life issues to develop strategies and implement actions that can decrease the lifecycle impact of automobiles in their last and perhaps least understood stage.

Keywords End-of-life vehicles · Dismantling · Recycling · Plastics

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1 Introduction

Automobiles are an integral part of today's society; however, there is growing concern over the impact that these products have throughout their life cycle. Automobiles in many ways represent an extreme form of *complex consumer products*, such as computers, that pose significant challenges in how to assess their benefits and impacts on the environment and society. Although the use and production phases of a vehicle's life cycle are the largest contributors to the negative life cycle impacts of automobiles (Puri et al. 2009), the end-of-life phase must also be considered in order to have a complete understanding of the total life cycle of these products. The aim of this chapter is to summarize end-of-life vehicle processes, legislation, challenges, and to predict future issues in order to provide this more complete understanding of the end-of-life vehicle phase. Finally, by predicting how emerging technologies may affect end-of-life vehicle management, this can provide valuable insights and information to vehicle manufacturers and recyclers to aid in the decision-making process.

2 End-of-Life Vehicle Management in Canada and the United States

Assuming 6 % of all registered roadway vehicles in use are retired annually and 6 % of all retired vehicles are abandoned (Staudinger and Keoleian 2001), an estimated 13 million vehicles are permanently retired and recycled in Canada and the United States annually (Sawyer-Beaulieu 2009). These end-of-life vehicles (ELVs) are managed within a network consisting primarily of dismantlers (salvage yards and junk yards, included), crushers, and shredders, and metal manufacturers.

ELV dismantling and shredding practices and post-shredder recovery/treatment processes will vary from region to region, as influenced by:

- regulatory constraints (federal, provincial/state, municipal);
- market supply and demand for ELVs and used car parts;
- market value of the particular parts recovered;
- supply and demand of ELV hulks as shredder feedstock;
- shredder feed material specifications (i.e., acceptable versus non-acceptable materials) and quality control (i.e., inspection, sampling, testing of materials destined for shredding);
- shredder through-put capacity;
- downstream shredded material processing methods/technologies;
- shredded metal product quality control;
- supply and demand of shredded ferrous metals as alternative melting units for steel mills and foundries;
- foundry and steel mill feedstock specifications and quality control;
- shredder residue (SR) processing/management options (Sawyer-Beaulieu 2009).

2.1 ELV Dismantling Practices

ELV dismantling business models will vary, but, in general, dismantling businesses are typically operated as "full-service" facilities, "self-service" facilities, or as a combination of full and self service, frequently referred to as "hybrid" facilities (Haddad 2008; Sawyer-Beaulieu 2009). Full-service facilities dismantle the ELVs they receive using in-house personnel, recover and inventory the resalable parts, as well as inspect, test and clean the parts as may be required prior to their sale. In self-service facilities (commonly called "UPIC" or "U-Pull-It" facilities), ELVs are placed into a yard where customers may come and pull the parts themselves using their own tools, and buy them at a reduced price (Sawyer-Beaulieu 2009).

When a vehicle reaches its end-of-life, it may be retired as a consequence of old age and/or poor mechanical and/or physical condition, rendering the vehicles incapable of operation on roads or highways (i.e. unable to pass safety certification). A vehicle may also be retired as a 'write-off' as a result of severe damage (by collision, impact, fire, or flood) or theft and dismantling (Sawyer-Beaulieu 2009).

Vehicles that enter the dismantling process may be obtained from a number of sources, including insurance companies, auctions, dealers and the public (ARC 2011b). The vehicles are typically inspected and evaluated by the dismantlers according to their make, model, model year, physical condition, and by the value and demand for particular automotive parts (Sawyer-Beaulieu 2009). They are consequently classified and managed as either "high salvage" (late-model, typical) vehicles or "low salvage" (old-age/early-model, typical) vehicles after entering the facility (refer to Fig. 1). The high salvage vehicles are typically late-model, accident/collision vehicles retired as vehicle write-offs (also referred to as total loss vehicles or TLVs) (Sawyer-Beaulieu 2009). High salvage-value parts are identified and their respective parts information and vehicle administration data is entered into computer-based parts inventory management systems (Fletcher 2011; Sawyer-Beaulieu 2009). Fluids and hazardous parts and materials are recovered and directed for reuse, recycling, energy recovery, and/or disposal.

Recovered fluids typically include refrigerants, antifreeze, gasoline, windshield washer fluid, lubricants—engine oil, transmission oil, differential fluid, brake-line fluid and power steering fluid—and, to a lesser extent, shock absorber fluid (Hoeher 2009a, b; Hoeher and Michael 2010; Sawyer-Beaulieu 2009). Lubricants may be shipped offsite for recycling using a licensed waste hauler, or alternatively, may be used by the dismantlers in on-site oil-fired space heaters for comfort heating. Recovered refrigerants, antifreeze, gasoline and/or windshield washer fluid may be reused on-site by the dismantlers, sold to customers for off-site reuse, or shipped offsite for recycling using a licensed waste hauler (Hoeher 2009a, b; Hoeher and Michael 2010; Sawyer-Beaulieu 2009).

Hazardous or environmentally sensitive parts and materials removed from ELVs by dismantlers typically include batteries, un-deployed air bags, tires, catalytic convertors, fuel tanks, mercury switches, and lead wheel weights

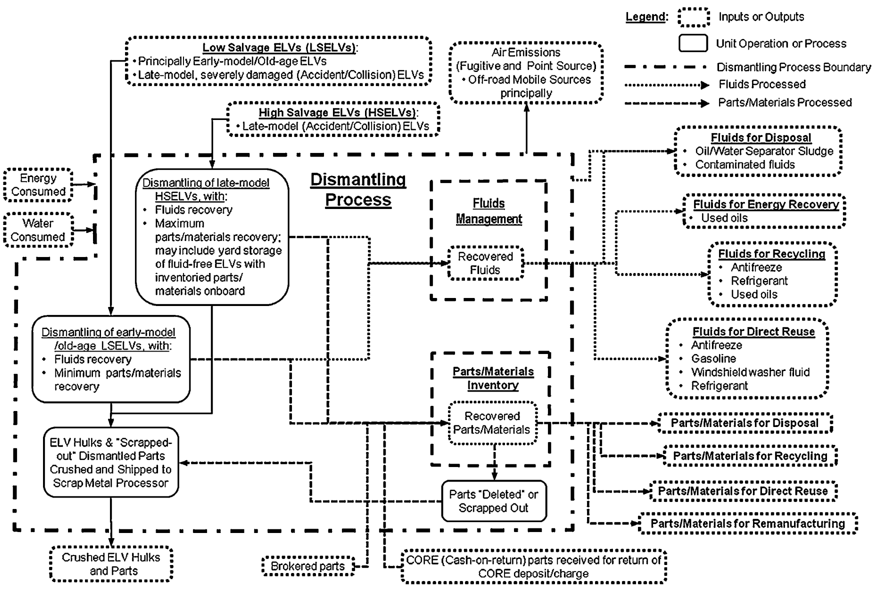

Fig. 1 Simplified dismantling process flow diagram (adapted from Sawyer-Beaulieu 2009)

(Keoleian et al. 1997; Staudinger and Keoleian 2001; Sawyer-Beaulieu 2009). Recovered batteries may be sold for reuse or directed for recycling. Un-deployed airbags will be either: (1) removed for reuse in jurisdictions that permit this, (2) deployed and left in the vehicles, or (3) removed, deployed and sent with the ELV hulks for shredding (Automotive Recyclers Association (ARA) 2011a; Canadian Council of Motor Transport Administrators (CCMTA) 2004; Sawyer-Beaulieu 2009). The recovery of automotive mercury-containing switches (i.e. hood/trunk convenience lights, ABS sensors) is largely performed under voluntary switch removal programs, such as the voluntary Switch Out Program coordinated by Summerhill Impact (former Clean Air Foundation) in Canada (Summerhill Impact 2011b), or National Vehicle Mercury Switch Recovery Program (NVMSRP) in the United States (End of Life Vehicle Solutions Corporation (ELVS) 2011). In some states, however, mercury switch recovery is required by law (i.e. Arkansas, Illinois, Iowa, Massachusetts, New Jersey, Rhode Island, Utah, Maryland, Indiana, North Carolina, South Carolina) (ELVS 2011). Tires are typically considered unacceptable shredder feed materials; they are usually removed by the dismantlers and either sold for reuse or sent for recycling (Staudinger and Keoleian 2001; Sawyer-Beaulieu 2009).

Parts removal and storage practices used by the dismantlers vary. Based on their assessment of the “principal” high salvage-value parts targeted for recovery and sale as reusable parts, some dismantlers remove these high value parts first, then place the “leftover” ELVs into inventory yards where inventoried parts are stored “on-board” the ELVs themselves for a certain period of time (Keoleian et al. 1997;

Staudinger and Keoleian 2001; Sawyer-Beaulieu 2009). This process allows the dismantlers access to other salvageable, but less popular parts, that are removed from the ELVs only after the higher value parts have been sold. Other dismantlers will strip any and all reusable parts identified for salvage, store only these parts, and not maintain yard storage of ELVs with on-board inventoried parts (Keoleian et al. 1997; Staudinger and Keoleian 2001; Sawyer-Beaulieu 2009). If the dismantlers do not have a particular part a customer is looking for, they may provide a "brokered part", a part brought in from another dismantler who has the part in inventory (Sawyer-Beaulieu 2009). Although dismantling is largely a manual process, power tools are used in preference to manual hand tools, wherever practical, and dismantlers often employ mechanized, semi-destructive dismantling techniques such as cutting, in which parts of negligible or lower value will be sacrificed to permit access to high value parts or assemblages (Sawyer-Beaulieu 2009).

Computer-based parts inventories are typically maintained and used to sell parts and to facilitate in deciding what to dismantle (Keoleian et al. 1997; Staudinger and Keoleian 2001; Recycling Council of Ontario (RCO) 1999; Fletcher 2011). Parts dismantled for reuse are each assigned an industry-wide interchange number that identifies which vehicle make, model and type it fits. The parts are then labeled with a bar code or inventory number, which is also entered into the computerized inventory management systems facilitating the tracking and locating of the parts in the dismantlers parts inventory or warehouse (Fletcher 2011). The computerized parts inventory management systems are typically interconnected through parts locator networks, connecting the inventory data of hundreds of auto recyclers across Canada and/or the United States. This permits an auto recycler to locate a part for a customer if the part is not available in the recycler's parts inventory (Fletcher 2011).

Prior to selling the parts to customers, dismantled parts are typically cleaned to remove dirt, oil and grease. To conserve water and reduce the amount of waste fluids generated, dismantling facilities commonly use closed-circuit parts washing systems: wash water is treated and reused within the system. Waste water generated as a consequence of water used in the dismantling process—typically oil/water separator sludge produced in a parts washing system—will be shipped by a contracted licensed waste hauler for off-site disposal (Sawyer-Beaulieu 2009).

Salvageable parts that are removed from the ELVs and determined to be unsuitable for sale as a reusable part, but are refurbishable, will commonly be sold by the dismantlers to parts remanufacturers (Staudinger and Keoleian 2001; Sawyer-Beaulieu 2009). Remanufacturable parts are generally referred to as "cores", analogous to an "apple core". An engine assembly, for example, that is tested and determined to be unsuitable for direct reuse may be stripped of reusable parts, leaving a "core" which itself may have value as a remanufacturable part (Sawyer-Beaulieu 2009). Parts commonly sold for remanufacturing include engines, starters, AC compressors, water pumps, carburetors, calipers, power steering pumps, carrier assemblies, windshield wiper motors, electronic control units (ECU), alternators, transmissions, axle assemblies and transfer cases (Johnson and Wang 2002; Sawyer-Beaulieu 2009).

Dismantlers will apply "Cash-On-Return" or CORE charges on certain part types (Sawyer-Beaulieu 2009). A CORE part is a part that may be received from a customer for return of a CORE deposit or charge. A "CORE charge" is a refundable deposit for the value of the CORE part that is paid at the time a "new" used part is purchased. The CORE part may be traded in for the credit of a portion of the price of the "new" used part being purchased (Sawyer-Beaulieu 2009). For example, instead of paying full price for a new part, such as an alternator, an old alternator can be submitted as a CORE and consequently reduce the price that the customer would have to pay for a "new" used alternator. CORE parts received by a dismantler will sometimes be sold as parts for reuse, but are most commonly sold with parts for remanufacturing, or directed for recycling with ELV hulks (Sawyer-Beaulieu 2009).

To facilitate the removal of the high salvage-value parts that the dismantlers target for recovery, other parts of little or no value may have to be removed first to make the desired parts accessible. Typically, these no-value parts are returned to the stripped vehicle and sent for shredding with other ELV hulks. Some stripped part types may not be returned to the ELVs, but will be shipped in segregated loads for shredding and metals recycling, e.g., steel or aluminum wheels (Keoleian et al. 1997; Staudinger and Keoleian 2001; Sawyer-Beaulieu 2009).

Periodically, dismantlers may perform an inventory clean-up. Dead or overstock parts inventory is removed, or "scrapped-out", and sent for shredding with the ELV hulks (Staudinger and Keoleian 2001; Sawyer-Beaulieu 2009). ELVs that are to be scrapped-out and have parts inventoried on-board are reviewed for salvageable parts to be kept. Those parts are removed from the ELVs and the remaining hulks are sent for shredding (Sawyer-Beaulieu 2009).

Dismantlers commonly compact their leftover ELV hulks, along with scrapped-out parts, prior to shipping them to the shredders using either their own on-site car crushers or contracted portable car crushers (Keoleian et. al. 1997; Staudinger and Keoleian 2001; Sawyer-Beaulieu 2009). Compaction maximizes the number of ELV hulks that may be shipped at one time at the most economical cost while satisfying shipment height restrictions, where applicable. Some dismantlers may ship their ELV hulks and scrapped out parts without crushing them because of their close proximity to receiving shredding facilities and their low ELV processing throughputs, e.g., two or less ELVs per day (Sawyer-Beaulieu 2009).

2.2 ELV Shredding

As of 2006, there were about 220 auto shredding facilities in the U.S. (Taylor and Toto 2006) and approximately 20 in Canada. As illustrated in Fig. 2, stripped ELV hulks and scrapped out parts that are shipped to shredding facilities in Canada and the United States are typically processed through hammer mill shredders along with other metal-rich scrap materials, in particular end-of-life appliances (ELAs) or "white goods", and construction, renovation and demolition waste (Keoleian et al. 1997; Staudinger and Keoleian 2001; Sawyer-Beaulieu 2009).

The fragmented material discharged from a mill is further processed typically using air separation of the low density, non-metallic materials from the higher density, metal-rich fraction. The metal-rich fraction is subsequently processed by magnetic separation to separate the ferrous metals (cast iron, carbon steel) from the non-ferrous and non-magnetic metals (aluminum, copper, zinc, nickel, stainless steel, and lead). The shredded ferrous metal product is recycled as alternative steel mill feed stock (Keoleian et al. 1997; Staudinger and Keoleian 2001; Sawyer-Beaulieu 2009).

The predominantly non-ferrous, non-magnetic metal fraction, containing high grade stainless steels (SS), as well as some low density, non-metallic materials, usually requires further treatment, for example, using a combination of screening, air classification and eddy current separation methods, to improve metals recovery

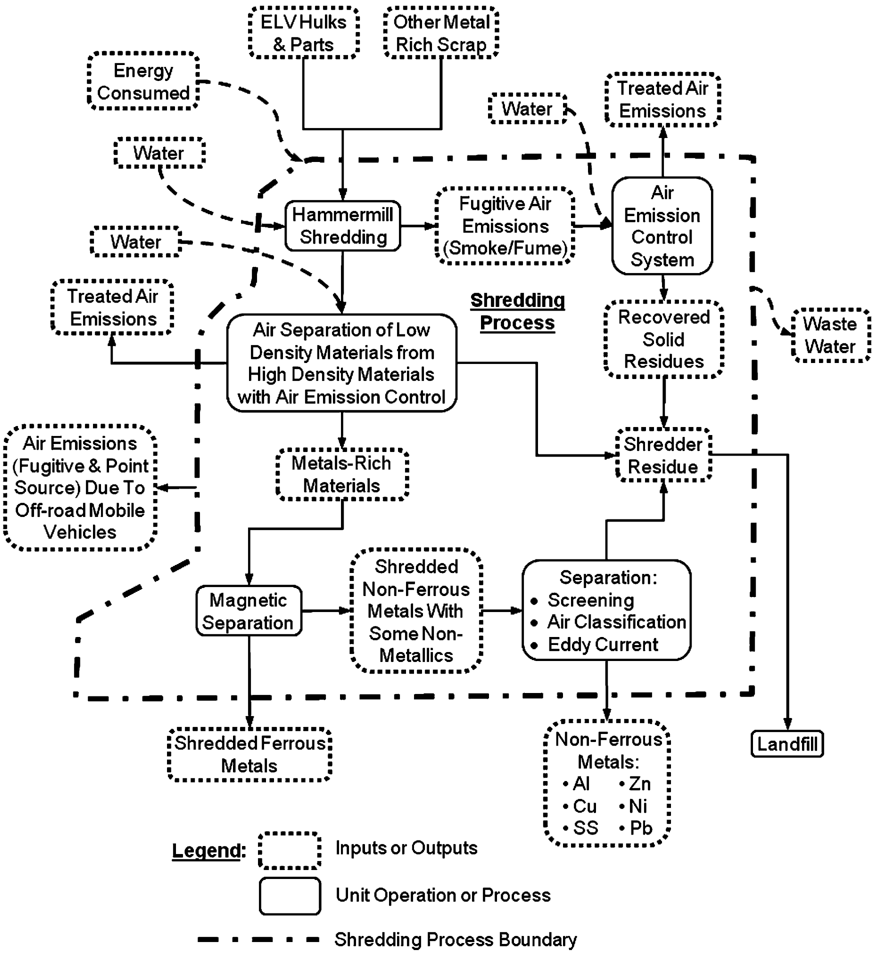

Fig. 2 Simplified shredding process flow diagram (adapted from Sawyer-Beaulieu 2009)

(Gesing et al. 1998; Sawyer-Beaulieu 2009). The resulting mostly non-ferrous metal product will typically be shipped to recycled metals processors for additional processing and treatment to separate the materials into individual metal fractions that are of sufficient purity for subsequent metal refining. The additional processing methods that may be used include, for example, screening, eddy current separation, heavy media separation, and air-fluidized sand-bed separation. The left-over, mostly non-metallic materials, i.e. the shredder residue (SR), is routinely disposed of by landfilling (Keoleian et al. 1997; Staudinger and Keoleian 2001; Sawyer-Beaulieu 2009).

Water will be strategically added into a shredding process in the mill and air separation/emission control systems in controlled quantities to control mill temperature, to prevent fire, reduce wear on mill parts and to help control fugitive air emissions generated by the process. The quantity of water that may be applied can vary from minimal quantities—for example just sufficient quantities to keep fires in check, i.e. "dry shredding"—to flooded conditions (i.e. "wet shredding") (Sawyer-Beaulieu 2009). The flooded conditions of wet shredding effectively prevents the generation and discharge of fugitive air emissions from the mill and, hence, avoids the requirement (and cost) for an air emission collection and control system. Wet shredding, however, results in mill discharge materials saturated with water requiring some sort of system for dewatering the materials and handling the waste water generated by the process. Further, the SR generated in a flooded shredding process is significantly heavier resulting in higher transportation and disposal costs (Sawyer-Beaulieu 2009).

Air emission control systems are typically required in shredding processes (except wet shredding) for collection and treatment of fugitive air emissions generated and discharged from a shredder mill, and in the air separation systems that remove the non-metallic materials from the heavier metals-rich stream (Institute of Scrap Recycling Industries (ISRI), Inc. 1998; Sawyer-Beaulieu 2009). The air emission control equipment commonly consists of at least an air cyclone separator for collecting larger particulates, and could include a wet scrubber for removing fine particulates, oil mists/fumes, etc. from the air stream (ISRI, Inc. 1998, Sawyer-Beaulieu 2009). Although not considered the best available technology (BAT), wet scrubbers are typically used in preference to air filtration systems for treating shredder air emission streams to avoid the risk of fire. Scrubber water is typically collected and recirculated, eliminating the need of waste water treatment and discharge (ISRI, Inc. 1998; Sawyer-Beaulieu 2009).

3 Regulation of ELV Management in Canada and the US

The ELV management industry is well established in North America and the processing technologies are generally understood, however the regulatory aspects of ELV management are not well-known/understood (Sawyer-Beaulieu 2009). Regulatory issues impacting ELV dismantling and shredding facilities can include:

- environmental site development licensing;
- facility/business operations licensing;
- business-related or operations-related compliance documentation and reporting;
- zoning bylaws restricting site use;
- management, control and permitting of environmental emissions (air emissions, noise, waste water and storm water discharges, hazardous waste disposal);
- environmental performance/compliance reporting.

The regulation of ELV management facilities in Canada and the United States is primarily focused on business and operating practices as opposed to the regulation of the retired vehicles themselves. The regulatory mechanisms that are applied include legal statutes, regulations, and bylaws, as well as voluntary mechanisms, such as best management practices (BMPs). The operations, activities and practices that are typically regulated and/or controlled in ELV management businesses include:

- emission of air contaminants, including noise;
- discharge of waste water (process and/or storm water);
- waste generation and disposal;
- site use and materials storage.

In addition, these facilities typically require business licensing (under provincial/state legislation and/or municipal bylaws), which permits them to carry out dismantling and recycling of ELVs. Municipal bylaws governing the licensing of ELV dismantling and recycling commonly stipulate site-use conditions or restrictions such as materials storage restrictions or site accessibility conditions (Sawyer-Beaulieu 2009).

ELV management companies in Canada and the United States are subject to business and environmental regulations, however the specific legislative criteria and mechanisms vary somewhat from jurisdiction to jurisdiction. For example, the use of used crankcase oils as fuel in used-oil fired space heaters, for comfort heating, is regulated in Canada and the United States.

In the Unites States, a permit or license is not required for the burning of used oil in used-oil fired space heaters as long as (1) the used oil is generated on site or collected from a "do-it-yourselfer" used oil collection center (DIYs), (2) the space heater used has a maximum capacity of 0.5 million Btu per hour or less, and (3) the combustion gases from the heater are vented to the ambient air (United States Environmental Protection Agency (USEPA) 1994; United States 2010). In Canada, the regulated use of used oil as a fuel varies slightly from province to province. In some provinces, facilities have to be permitted or licensed (e.g. Certificate of Approval) to use used-oil fired space heaters, and only equipment approved by the Canadian Standards Association (CSA) and Underwriters' Laboratories of Canada (ULC) may be used. In some provinces small used-oil generating businesses are exempted from the permits required by larger sites if they register (allowing them to use used-oils as fuel), and they do not exceed specified maximum use rates (e.g. 15 liters per hour per premises) and the used oil-fired heater conforms to specified equipment standards (e.g. CSA) (Environment Canada 2005, 2011; New Brunswick 2002).

The management of end-of-life vehicles (ELVs) in Canada and the United States is largely a market driven industry, with used parts and scrap metal prices driving high recycling rates (ARC 2011b). With the exception of British Columbia, there is no jurisdiction in Canada and the United States where ELV management activities are legislated. British Columbia's Vehicle Dismantling and Recycling Industry Environmental Planning Regulation (VDRIEPR) requires a dismantler processing 5 or more ELVs per calendar year to establish, register, follow and maintain an environmental management plan (EMP) for the ELVs they process (British Columbia 2007). The EMP must describe how prescribed wastes (liquids, refrigerants, batteries, mercury switches and tires) are removed, stored, treated, recycled and/or disposed. It must also define management processes for minimizing or eliminating the discharge of waste to the environment (British Columbia 2007). The VDRIEPR also outlines auditing and reporting requirements for vehicle dismantlers. Every five years, a dismantler's EMP must be reviewed, amended and approved by a qualified professional (as defined under the regulation). Every two years, each vehicle dismantler must be audited by a qualified professional and an audit report prepared confirming how the prescribed wastes were managed, if they were managed in accordance with the facility's EMP and how effective the facility's management processes are in minimizing or eliminating the discharge of wastes to the environment. (British Columbia 2007; British Columbia Ministry of Environment (BCMOE) 2008).

A number of industry standards or codes of practice are being used in the dismantling and metals recycling industries that help to regularize ELV recycling practices. Recycled parts grading guidelines, standardized part type definitions and descriptions, and part damage location and identification codes, developed by the Automotive Recyclers Association (ARA) (ARA 2006, 2011b) have been adopted on an international scale and are built into auto recyclers' inventory systems (Fletcher 2011). These parts identification and grading codes have been established for automotive body panel parts and mechanical parts and facilitate recycled parts quality control.

The Canadian Council of Motor Transport Administrators (CCMTA) guidelines for use of recycled original equipment air bags outline procedures to safely re-use "recycled", i.e. non-deployed, OEM airbags, in jurisdictions where it is permitted (ARC 2011a; Canadian Council of Motor Transport Administrators (CCMTA) 2004).

In 2008, the National Code of Practice was established for automotive recyclers participating in Canada's National Vehicle Scrappage (Retire Your Ride, http://www.retireyourride.ca/home.aspx) Program (Automotive Recyclers of Canada (ARC) 2008; Summerhill Impact 2011a). Created by the Automobile Recyclers of Canada (ARC) for Environment Canada, the code required all automotive recyclers enrolled in the program to comply with applicable legal requirements, e.g. de-registration of vehicle identification numbers (VINs), as well as with environmental management practices specified under the Code, including:

1. recovery, storage, transportation, manifesting, disposal and/or record keeping requirements for waste fluids (including refrigerants), lead acid batteries, mercury-containing switches, lead wheel weights, and other hazardous materials or components;
2. training in practical best management practices (BMPs);
3. vehicle processing area requirements (i.e. vehicle receiving, dismantling, hulk storage, crushing, "wet parts" storage, hazardous fluids storage); and
4. facility audit requirements to ensure compliance with the code.

When the National Vehicle Scrappage Program terminated March 31, 2011, 137,783 vehicles had been permanently retired and processed by 335 participating recyclers across Canada (Summerhill Impact 2011b).

Although extended producer responsibility (EPR), or product stewardship, practices have not been legislated for ELVs managed in Canada and the United States, EPR based initiatives have been launched for ELVs and/or ELV derived materials, or are under consideration. Canada's Switch Out Program and the NVMSRP in the United States (ELVS 2011; Summerhill Impact 2011b), for example, are EPR-based partnerships between automotive manufacturers, automotive recyclers/dismantlers, scrap metal recyclers, and steel manufacturers, committed to the recovery and recycling of automotive mercury-containing switches from ELVs and hence reducing the release of mercury to the environment (Summerhill Impact 2011b; USEPA 2006). Quebec currently has EPR programs for mercury switches, used oil and used oil filters with plans to add programs for used tires and automotive electronics in the near future (ARC 2011b; Quebec 2008).

In 2009, the Ontario Ministry of the Environment outlined proposed EPR-based changes to Ontario's waste diversion framework, which would include the banning of ELVs and ELV-derived materials from landfill disposal, with proposed five-year material-specific collection and diversion targets (Ontario Ministry of the Environment (OMOE) 2009). The proposed EPR-based waste diversion system would make individual producers (manufacturers, brand owners, or first importers of products or packaging made with a designated material) responsible for meeting diversion outcomes (OMOE 2009).

More recently, EPR-based, environmental management system (EMS) standards have been proposed for ELV management in Ontario (Ontario Automotive Recyclers Association (OARA) 2011), as well as for ELV management across Canada (ARC 2011b). These proposed provincial and national standards are based on the use of the National Code of Practice that was established for automotive recyclers that participated in Canada's National Vehicle Scrappage Program (ARC 2008). The proposed ELV EMS standards would require all ELV processors to be licensed, authorized or certified under provincial law, and subject to a common decommissioning standard (codified in provincial law) to minimize environmental discharges and ensure proper treatment of substances of concern. It is suggested that the proposed standards would help to level the playing field for businesses in the ELV management industry, while maintaining the market-driven, competitive structure of the automotive parts and materials recycling industry (ARC 2008; OARA 2011).

4 Closed-Loop Recycling and Plastics in End-of-Life Vehicles

As vehicle manufacturers strive to improve the fuel economy of vehicles, reducing vehicle weight has become increasingly important. Many plastics are economical, easy-to-manufacture materials that can reduce the weight of components that have historically been produced from materials such as metals. Figure 3 shows how the weight of plastic within vehicles has increased since 1985, with plastics contributing the second largest weight percentage of material, behind only ferrous metals (Ferrão and Amaral 2006a; The Society of Motor Manufacturers and Traders Limited 2011). However, plastics are difficult to recover when a vehicle reaches the end-of-life phase. Plastics can be used in vehicle parts or locations that are difficult to access. This situation is often made more complex when plastics are joined or fused with other plastics, making them difficult to economically separate. Challenges in recovery therefore hinder actual recycling.

Recycling can be divided into four main categories; closed-loop recycling, downgrading, chemical or feedstock recycling, and energy recovery (Hopewell et al. 2009). Closed-loop recycling is what most people envision when they hear the term “recycling”. In closed-loop recycling, the materials from an end-of-life product are used to produce a new product with equivalent properties (Hopewell et al. 2009; Chilton et al. 2010). Thus, the recycled materials have more value than if they were simply used to replace cheap filler materials (Palmer et al. 2009).

Recycling materials so that they can produce products with equivalent properties is an ideal situation. However, it is difficult to achieve equivalent properties in recycled materials as compared to virgin materials. Plastics age and this impacts

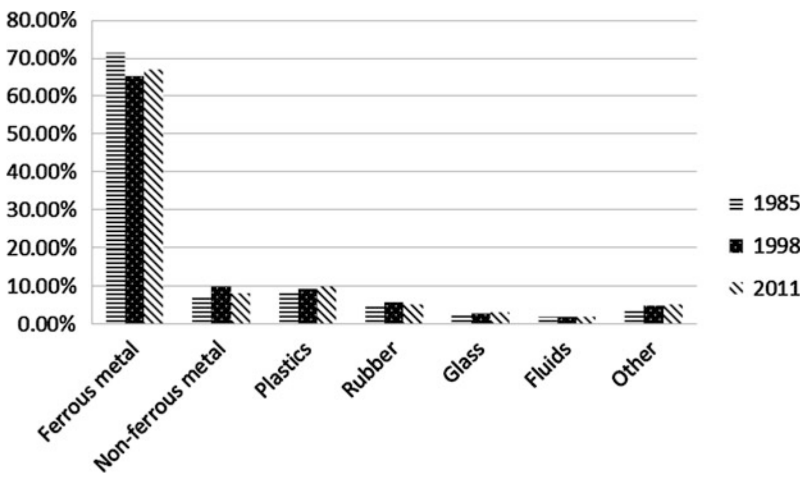

Fig. 3 Materials in an automobile (1985, 1998, 2011). Adapted from: 1985 and 1998 (Ferrão and Amaral 2006a), 2011 (The Society of Motor Manufacturers and Traders Limited 2011)

Table 1 Elongation at break for ABS and HDPE after extrusion and after ageing and extrusion cycles

Material	ABS[a]	HDPE[a]
Elongation at break (after 1st extrusion)	9 %	750 %
Ageing conditions	72 h at 90 °C	48 h at 110 °C
Number of ageing and extrusion cycles	6	10
Elongation at break (after ageing and extrusion cycles)	3 %	770 %

[a] *Sources* ABS (Boldizar and Möller 2003), HDPE (Boldizar et al. 2000)

the long-term behavior of products made from these materials (Struik 1977). Furthermore, the recycling of plastics involves not only aged plastics, but also plastics that have been extruded multiple times.

Studies on ABS, PP, and HDPE have tried to simulate the effects of aging and extrusion that occur during the recycling of plastic materials (Boldizar and Muller 2003; Boldizar et al. 2000; Strömberg and Karlsson 2009) (see Table 1). Table 1 shows that the combined effects of aging and recycling on the mechanical properties of various plastics is not consistent. Furthermore, industrially recycled polymers have shown poorer mechanical properties than those measured during simulated recycling conditions (Strömberg and Karlsson 2009).

Furthermore, the contamination of materials (i.e. from different plastics, fillers, pigments, additives) produces plastics with degraded properties. Material contamination can result in plastics with low tensile strength, mixed colour, and decreased transparency (Astrup et al. 2009). Thus, recycled plastics are often blended with virgin plastics in order to ensure that the resulting material has desirable properties (Astrup et al. 2009).

Although there are technical challenges to closed-loop recycling of plastics, studies have shown that from a life-cycle assessment viewpoint, closed-loop recycling of polyethylene terephthalate (PET) bottles results in an overall reduction in emissions of key pollutants studied, as well as a reduction in the overall environmental impact, as compared to recovering the PET waste and burning it in an energy-from-waste facility (Chilton et al. 2010); however, the economic implications were not studied. Studies that have looked at the economics of recycling ELV parts have shown that it may not be economically justifiable to recycle these parts, and is dependent on the marketplace demand for recycled materials (Bellmann and Khare 2000).

5 Other End-of-Life Recycling Options to Improve Sustainability

Downgrading refers to plastics that are of lower quality than virgin plastic. This may be due to contamination of different plastics, fillers, additives, colors, etc. Certain properties that can be affected are the tensile strength, transparency, and colour of the plastics (Astrup et al. 2009). These plastics are often used as fillers in products such as pallets, fences, and garden furniture.

Chemical or feedstock recovery has the advantage of producing valuable and useful products that can be used to make new petrochemicals or plastics (Al-Salem et al. 2009). Methods that enable chemical or feedstock recovery include pyrolysis, gasification, and solvolysis (Zia et al. 2007; Sasse and Emig 1998). In pyrolysis, a material is heated to a controlled temperature, in the absence of oxygen, causing volatile organic materials to decompose into gases and liquids. In the case of automotive parts, the volatile organic materials would be the plastics and rubbers used in the components. The other materials (metals, glasses, etc.) remain unchanged and can be separated from the organic matter (de Marco et al. 2007). The organic gases and liquids obtained through pyrolysis can be used as fuels or as a source for organic chemicals (Buekens and Huang 1998). In this way, the basic elements from ELV plastic components are reused. A benefit of this method of reusing polymeric materials is that the shredder residue (SR), which is produced when ELVs are shredded, can be pyrolised and the different types of plastics do not need to be separated from each other. In the gasification process, a material is also heated to a controlled temperature; however, it is in the presence of air (Al-Salem et al. 2009).

Solvolysis is a term used to describe the depolymerization process in which the original monomers are produced from the materials. Various types of solvolysis include hydrolysis, glycolysis, and methanolysis (Sasse and Emig 1998), in which polymer chains are cleaved by reagents such as water, glycols, or methanol, respectively (Sinha et al. 2010). It should be noted that the polymers used in these processes should be sorted and precleaned.

In energy recovery, waste plastics are incinerated and the heat is recovered. This heat may be used to heat a space or can be used to generate power (Eriksson et al. 2005). Also, using SR as fuel in a blast furnace has shown promising results (Mirabile et al. 2002). An advantage of energy recovery methods is that separation of the various plastics is not necessary. However, SR is non-homogeneous and the energy content can vary.

Polymer composites further complicate the recyclability of automotive materials. Composites are materials composed of two or more constituent phases (Vidal et al. 2009). Polymer composites have a polymeric matrix and a reinforcement or filler phase. In the case of composites, a combination of the various types of recycling may be utilized. Mechanical recycling of composites breaks down the composites by mechanical means and then separates resin-rich powder products from fiber-rich fibrous products. These materials can be reintroduced into new composites as fillers and reinforcements; however, these products are low-value applications. Another method, fiber reclamation, is particularly useful for carbon fiber reinforced composites. In fiber reclamation, thermal or chemical processes are used to break down the polymeric matrix and the fibers are released and collected. Chemical and/or energy recovery of the matrix is possible (Towle 2007). Furthermore, composites can be produced using reclaimed carbon fibers. The recycled carbon fibers have exhibited a high retention of mechanical properties (Towle 2007).

Bio-based, biodegradable materials offer an additional end-of-life treatment method: composting. Kim et al. (2008) have reported that composting of an automobile component made from a fiber reinforced biocomposite is a more favorable waste management scenario than landfilling the materials.

6 Sorting and Separating Plastics

The recycling process creates shredder residue which in turn contains the polymeric materials to be recycled. These various polymers may be used to generate energy or fuels, in which case, it is not necessary to separate. However, energy recovery scenarios have not been shown to be promising in meeting EU recycling targets of 85 %, due to stringent regulatory requirements (Ferrão et al. 2006c).

If the polymers are to be recycled into polymers to make new products, they must first be separated, cleaned, and free of contaminants. Usually, separation is thought of as parsing distinct materials from one another, such as in “blue box” or curbside collection programs of recyclables. Simple recyclable items, such as water bottles, newspapers, etc., may be co-mingled, but inherently are not attached to one another. Automotive plastic parts are unlikely to be so simply configured. They often combine multiple plastic types and various fastening or joining methods. The recovery of automotive plastics therefore means that separation must be thought of in two aspects: (1) liberation; and (2) actual separation of materials from one another.

In terms of the latter, separation, there are many different methods of separating materials. Dalrymple et al. (2007) have listed screeners; air and water classifiers; density, electrostatic, and magnetic separators; and flotation systems as examples. It has been reported (Jody and Daniels 2006) that mechanical separation techniques are able to separate inorganic fines and residual metals from shredder residue, producing a polymer concentrate. Polymer separation techniques (i.e.: froth flotation) are then able to separate and recover polyolefins and engineered plastics (i.e.: ABS) from the polymer concentrate. A mixed-rubber fraction can also be separated and recovered using dry and wet processes (Jody and Daniels 2006). But to have separation, it is often assumed that different materials are no long *co-joined* to one another.

In terms of the former, liberation, size reduction through separation is often the most common operation. Breaking items down into smaller pieces should also liberate one material from another (Loehr and Melchiorre 1996) because bonds between different materials should be broken, be they adhesive in nature, welded, or bound by fasteners. The study of liberation as it applies to complex consumer goods has been relatively limited. Jekel and Tam (2007) showed that accepted ways of modeling how plastics could break down for eventual separation were not readily applicable or had limited value. The advantage of such a classification is that if plastics breakage could be predicted, designers and engineers could then exploit this to created plastic parts that are ultimately more recyclable. A key challenge to increasing the recovery of waste automotive plastics is how one plastic type can be liberated from another prior to applying various separation technologies.

To enhance the liberation of one material from another, some work has been performed using cryogenics to study the liberation of plastics from metals or other non-plastics during the recycling of ELVs (Gente et al. 2004; Dom et al. 1997). There is the potential of using differences in the behavior of plastics at cryogenic temperatures to aid in the separation of various plastics during ELV recycling. In addition, Barsha and Tam (2009) argue that the actual unit operation used in size reduction can play a far more significant role in whether or not plastics can be liberated from one another. Thus, results from one shredding operation in one facility may not be equal to results that are obtained in another facility. A successful design-for-environment effort to consider recovery in advance will require detailed knowledge of how a part or material will be handled at its end-of-life.

Sorting and separating plastics from shredder residue is not currently economical. In order to meet the 2006 EU requirements for ELVs (European Union 2000), Ferrão and Amaral (2006a) have shown that more thorough dismantling of plastic components from vehicles was sufficient; however, to meet the 2015 requirements, it has been suggested (Ferrão and Amaral 2006a) that separation technologies must be upgraded. Nevertheless, from an economics standpoint, the products liberated from the separation processes must have value in the marketplace.

7 Effects of Emerging Technologies on the Recyclability of End-of-Life Vehicles

Given the challenges of recycling polymeric materials at the automotive end-of-life phase, how will emerging technologies in automobiles affect the use of polymers? Reducing noise and vibrations to improve customers' driving experience, lightweighting of vehicles to reduce fuel consumption, and designing components that are more sustainable or environmentally preferable all affect the amount and types of polymers used in future vehicles.

Polymers, due to their viscoelastic nature, have been successfully used to damp noise and vibrations within vehicles (Rao 2003). Advances in technology now allow the cost effective mass production of multilayered laminate structures and spray-on dampeners (Rao 2003). This provides customers with the vehicle quality and performance that they expect from their vehicles. Nevertheless, these materials are quite difficult to separate at the end of a vehicle's useful life.

Bio-based polymers and composites are increasingly being used in vehicles (Suddell 2007). These materials are lightweight and can be used in many different applications within a vehicle (Kim et al. 2008). As well, they have the added benefit of being more environmentally preferable than traditional petroleum-based polymers (Kim et al. 2008). These materials also have the potential of being

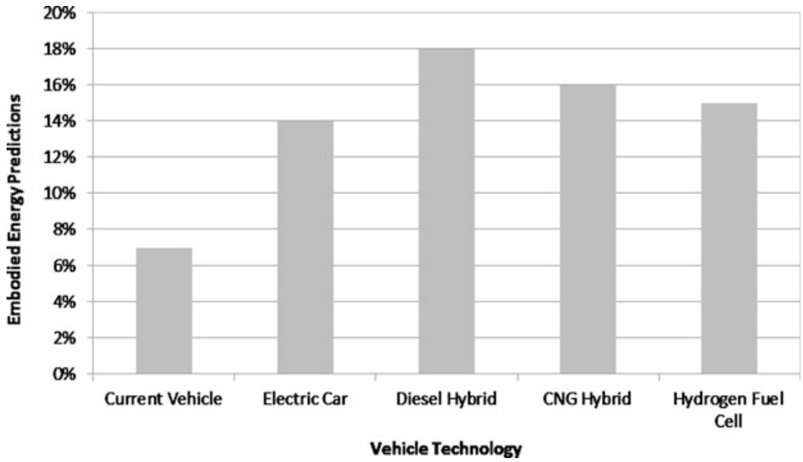

Fig. 4 Predictions of embodied energy (as a percentage of the life-cycle energy use) of vehicle technologies in the year 2020, based on a recycling rate of 95 % for metals and 50 % for plastics; adapted from Weiss et al. (2000)

collected and composted at the end-of-life phase. This can provide further environmental benefits from a lifecycle analysis perspective (Kijchavengkul and Auras 2008). Nevertheless, these bio-based materials add additional complexity to the number of different materials that must be sorted and separated during the recycling of a vehicle.

Emerging fuel technologies can also affect the lifecycle impacts of vehicles. Weiss et al. (2000) have shown that the embodied energy within the materials used in the production of vehicles can vary greatly, depending on the vehicle technologies (see Fig. 4). As vehicle technologies develop and new materials are used, or lightweight materials are used more extensively, the embodied energy within the vehicle materials changes. Furthermore, whether the materials used are virgin materials or recycled materials also have an effect. For the values displayed in Fig. 4, a recycling rate of 95 % for metals and 50 % for plastics has been assumed. These rates are not currently achieved in practice, but it has been assumed that they will be by the year 2020 (Weiss et al. 2000).

8 Considering the End-of-Life Phase for Vehicles During the Design Process

The method in which a component is manufactured or assembled can also affect the ease of recyclability of the vehicle from which it comes. Design for recycling (DfR) is a method in which end-of-life recyclability is considered during the design of a product. In the case of automobiles, Ferrão and Amaral (2006b) have shown that in order to meet increased recycling rates, dismantling, shredding, and post-shredding activities must occur. Consequently, automobile manufacturers are starting to adopt DfR principles during the process of designing their products (Gerrard and Kandlikar 2007).

As suggested by Ferrão and Amaral (2006a), there are two strategies available to increase the recycling rate of the constituent materials of shredder residue:

1. Decrease the amount of shredder residue created by more thorough dismantling of the complex products; and
2. Upgrade the sorting and separation technologies for shredder residue, and determine recycling possibilities for the materials collected through separation.

The first strategy can be aided by implementing design for disassembly (DfD) principles during the design process for new products. From a materials perspective, design for disassembly rules include minimizing the number of different materials used, using recyclable materials, and eliminating hazardous materials when designing products (Bogue 2007). To target the second strategy listed above, proponents of design for disassembly principles suggest that if multiple plastics must be used, their densities should differ by at least 0.3 (Bogue 2007). This enables the technique of separating plastics based on density to be more effective.

Using DfR software, it has been shown that dismantling tires, bumpers, glass, fuel tanks, and seats from vehicles can increase the recycling rate from 77.3 to 86.2 % and reduce the amount of materials that must be disposed by 42 % (Santini et al. 2010). This demonstrates the necessity of modifying current vehicle waste management techniques as well as designing vehicle assemblies to make their end-of-life dismantling more efficient and economical.

9 The Future of End-of-Life Vehicle Recycling

There are many challenges facing automobile manufacturers, dismantlers, and recyclers. Nevertheless, there is much that can be learned from other industries. For example, waste electrical and electronic equipment (WEEE), end-of-life aircraft, and end-of-life vehicles are all complex products which contain many different materials, including ferrous and non-ferrous metals, polymers, and composites. These materials must be managed when the products have reached their end-of-life.

Each sector has its own issues and concerns in regards to end-of-life recycling of plastics. Recyclers of WEEE must contend with many different consumer products, manufacturers, plastics, collection locations, and hazardous compounds (Schlummer et al. 2007; Schluep et al. 2009). By comparison, the collection of vehicles for recycling is better documented and reported (The Alliance of Automobile Manufacturers 2011), ELVs contain many different plastics, and there is a large volume of plastics in each vehicle. Finally, recycling of end-of-life aircraft is centralized and there are fewer different models of aircraft recycled (Michaels 2007; de Brito et al. 2007), as compared to WEEE and ELVs. However, predictions of future aircraft are that up to 50 % of the unladen weight in their primary structures will be composed of polymeric composites, mainly carbon fiber reinforced composites (Towle 2007). Composites are inherently difficult to recycle due to issues such as their complex composition, cross-linking of thermoset resins, and their combinations with other materials (Pimenta and Pinho 2011).

Much research has been performed in the various sectors to study how these products can be recycled more efficiently and economically (Kahhat et al. 2008; Schluep et al. 2009; Kim et al. 2004; Dalrymple et al. 2007; Towle 2007) and knowledge gained in one sector can benefit all sectors.

As discussed previously, emerging technologies may also add to the complexity of recovering ELV materials. Thus, DfR and DfD strategies must be embraced by vehicle manufacturers in order to account for all materials during the entire life cycle of their products. This design approach will ensure maximum recovery of materials as emerging technologies are introduced into new vehicles and vehicle complexities increase.

Finally, when life cycle assessments of end-of-life vehicles or components have been performed, there is general consensus that recovery of materials for recycling and/or energy recovery is the most environmentally preferable option (Puri et al. 2009; Duval and MacLean 2007), although waste-to-energy applications result in the consumption of resources that are predominantly non- renewable (e.g. petroleum-based plastics). There may not be one solution that best meets all of the challenges faced by ELV management, especially when predicting the handling of vehicles containing emerging technologies (e.g., electric vehicles, bio-based materials, laminated materials); however, a combination of technologies could provide more sustainable solutions.

Developing and implementing technologies for the recovery of ELV plastics prior to shredding could be simpler and of greater benefit than post-shredder ELV plastics recovery technologies. Rather than shredding the entire hulk with minimal prior hand disassembly, alternative "dismantling techniques or strategies" may be identified for recovering ELV parts/materials for recycling prior to shredding. For example, intermediate or limited separating processes (e.g., breakage, cutting, comminution) may be able to liberate additional items, which then may be processed by secondary or even tertiary processes (Sawyer-Beaulieu 2009).

Previous research on the economics of automobile dismantling under the 1990s North American recycling market (Johnson and Wang 2002; Spicer 1997) deemed disassembly of non-metallic components to be labor intensive and generally uneconomical. More recently, however, researchers are using industrial engineering systems approaches to model and assess the viability of "selective" or "targeted" parts dismantling and recovery scenarios, particularly for parts having high plastics content (e.g., automotive seat assemblies) (Barakat 2011), with the goal of reducing the amount of shredder residue requiring landfill disposal.

It will take a combination of government legislation, vehicle DfD and DfR advancements, technological advances in materials separation, and the implementation of more thorough dismantling procedures to make ELV recycling environmentally and economically sustainable.

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