Sustainability of the automotive recycling infrastructure: review of current research and identification of future challenges

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Abstract: In addition to rising fuel prices, government policy-makers are endeavouring to reduce the environmental impact of the automotive industry through directives and standards. Automotive manufacturers are working to reduce the use phase environmental impact of automobiles by introducing innovative vehicle designs. However, these product design changes may jeopardise the profitability of the business entities within the automotive recovery infrastructure leading to deleterious environmental impacts. This paper focuses on describing past research relative to the automotive recovery infrastructure and those research challenges that may arise in the future. The aim is identify the research gaps in order to ensure the sustainability of the recovery infrastructure.

Keywords: automotive industry; product recovery; recycling infrastructure; sustainability, future vehicular material composition; new powertrain technologies.


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1 Introduction

Automobiles are frequently a magnet for environmental criticism owing to their high visibility, carbon-based fuel usage, tail-pipe emissions, and hazardous material content. Automotive manufacturers are also faced with government policies (e.g., Engine Emission Standards, Corporate Average Fuel Economy (CAFE) (2000) regulations, and Reduction of Hazardous Substances Directive (RoHS, 2002/96/EC)), rising fuel prices, and changing consumer preferences. In response to these factors, for several decades the auto industry has been undertaking changes in the material composition (more aluminium and other light-weight materials) and powertrain technologies (e.g., hybrids and fuel cells) of its vehicles. The aim of these changes has been to reduce the environmental impact of the vehicle during the use phase. What is unknown, however, is the effect that these changes will have on the vehicle recycling infrastructure in the USA and elsewhere.

In Europe and Japan, where landfill space is often at a premium, heavy emphasis is placed on the efficient management of End-Of-Use Products (EOUPs) or vehicles that are commonly known as ELV in the literature. The ELV Directive (ELV, 2000/53/EC) is bringing about dramatic changes in the infrastructure associated with ELV recovery and recycling. The directive calls for increasing the recovery rate of materials from an ELV to 95% (by weight) by 2015. At some point, this may necessitate large scale vehicle disassembly and recycling of virtually every component. Ultimately, whatever costs are associated with the recovery/recycling of ELVs will be internalised and passed on to consumers. Another concept of growing importance is Extended Producer Responsibility (EPR), where an Original Equipment Manufacturer (OEM) assumes responsibility for a product throughout its life cycle. Both the ELV Directive and the EPR concept are driving OEMs to rethink traditional product paradigms and business models, and perhaps even restructure the relationship among the OEM, the ELV recovery infrastructure, the consumer, and other stakeholders.

In the USA, the infrastructure associated with the recovery and recycling of ELVs is almost entirely profit driven. All enterprises within the recovery infrastructure (e.g., dismantlers and shredders) must be profitable to stay in business. In response to concerns and regulations relating to the vehicle use stage, automotive OEMs are exploring innovative new powertrain technologies and the use of lighter-weight materials. One of the challenges associated with such explorations is to understand their effect on the resulting economic sustainability of the automobile recovery/recycling infrastructure. For example, as the plastic content in vehicles increases, will a company that profits from recycling the ferrous content in a vehicle survive? Certainly, it is undesirable for large segments of the ELV recovery infrastructure to economically collapse, as this would result in wide-spread accumulation of scrap vehicles. With this in mind, this paper focuses on describing the ELV recovery infrastructure and research characterising the infrastructure, understanding the potential vehicular changes that will affect the infrastructure, and identifying the associated research needs.

First, an overview of the life cycle of a vehicle in provided with emphasis on describing the material flows and economic exchanges within the automotive recovery infrastructure. This overview will also include a discussion on the differences and similarities of the recovery infrastructure in the USA, Europe, and Japan. Then work done by past researchers in describing the automotive recovery infrastructure is presented, with the aim of understanding the current knowledge gaps. Following this discussion, on-going and potential changes within the industry will be identified, and the
potential impact of these changes on the environmental and economic sustainability of the recovery infrastructure will be examined. Finally, some research challenges that may surface in response to these changes will be presented.

2 Background

Figure 1 shows a simplified diagram of the vehicle life cycle. As shown in Figure 1, after the raw material is extracted, it is processed, manufactured into parts and products, and then sold to the consumer. It should be noted that there is a chain of part and component suppliers that contribute to the final manufacturing/assembly stage performed by the OEMs. Traditionally the design of the part/components has mainly been the responsibility of the OEMs. Recently, however, manufacturers have begun to shift design responsibility to part/component suppliers. After the manufacturing stage, the vehicle spends a long period of time in the use phase of the life cycle. In the past, the median life of a vehicle has been reported to be 12–13 years (Libertiny, 1982, 1993). Lately, the median life has increased to around 16 years with as many as 5% of the vehicles still remaining on the road after 30 years of operation (Davis, 2004).

Figure 1  Automotive life cycle

When a consumer decides that they no longer wish to use a given vehicle, there are a number of options available to them:

1. sell the whole vehicle to another user
2. disassemble the vehicle with some components/modules reused
3. remanufacture the vehicle
4. recycle the vehicle for material content, and/or
5. dispose the vehicle to a landfill (Zussmann et al., 1994; Kumar et al., 2005).

The option selected depends on the economic benefit to the parties/entities associated with each option. It should be noted that often times a vehicle undergoes multiple use cycles (i.e., the first option is selected repeatedly) before the user considers the other options. After multiple use cycles, the value of the vehicle to the user (and other potential users) approaches zero. This is because the vehicle no longer functions as desired – the vehicle is said to have reached the end of its life. However, from the perspective of a dismantler or shredder, the value of the vehicle is not zero because they are not directly
interested in the vehicle function; rather, they are interested in the value of the vehicle subassemblies, parts, and materials (Kumar et al., 2007). It should be noted that the expression ‘EOUP’ is preferred over the commonly used ‘ELV’ phrase, because as a whole the vehicle may no longer be functional, but certain subassemblies or parts may be functional and of course the material can always be recycled for the secondary materials market.

Each life cycle stage shown in Figure 1 consumes certain amount of energy, and produces air/water emissions and municipal solid waste. Figure 2 shows the contribution of each stage in terms of energy consumption, air and water emissions, and municipal solid waste. As can be seen from the figure, use stage is the most significant contributor in terms of energy consumption, and air and water emissions. This justifies the effort of the automotive manufacturers to use lighter-weight material and new powertrain technologies in its vehicles. However, while analysing the impact of use stage on the environmental performance of a vehicle, it is important to note that the associated energy consumption and emissions are distributed over a larger period of time as opposed to a shorter time periods during the other stages (Field et al., 2001). Thus, any conclusion with respect to the environmental performance should carefully include the temporally distributed nature of emissions. It can also be seen from the figure that in terms of municipal solid waste, the EOUP stage was found to be the significant contributor.

Figure 2  Comparison of energy, air emission, water emission and municipal solid waste across the life cycle of 1995 generic vehicle

![Graph showing energy, air emissions, water emissions, and municipal solid waste](image)

Source: Adapted from Sullivan et al. (1998)

It should be noted that the choice of material plays an important role on the fuel economy of the vehicle. For example, use of lighter-weight material such as aluminium as opposed to steel is usually considered a positive choice in terms of fuel economy (Ungureanu, 2007a). As an approximation, a 10% reduction in mass produces a 5% improvement in fuel economy. However, it should also be noted that lighter-weight materials might not always be the most sustainable choice from a total life cycle perspective. For example, in a study to determine the potential benefits of lighter materials such as aluminium, it was found that substantial change in the existing manufacturing and assembly technologies would be needed. It was found that the current equipment and processes are well suited for steel-based components and a complete redesign of this equipment and processes would be needed to manufacture aluminium
components (Ungureanu, 2007b). Selection of material and manufacturing technology also impacts the automotive recovery infrastructure. A discussion of the impact of vehicle material composition and manufacturing technology on the automotive recovery infrastructure is provided later in the paper.

2.1 The automotive recycling infrastructure

The automotive recycling infrastructure consists of three major business entities:

- dismantler
- shredder
- non-ferrous operator.

About 95% of the automotive EOUPs enter the recycling infrastructure, which is considerably more than other products (see Figure 3). Of the EOUPs that enter the infrastructure, approximately 84% by weight are recycled (Ward’s Communications, 2006). The 15% of the mass that is not recycled ends up in a landfill in the form of Automotive Shredder Residue (ASR), which may contain substances like urethane, foams, fabrics, vinyl upholstery, padding, rubber, plastics, polymer composites, glass, sand, dirt, gravel, and wood (Klepner et al., 1999). Apart from this, there is also a chance that ASR will contain toxic materials such as Polychlorinated Biphenyls (PCBs) and heavy metals from electronic parts. The amount of ASR that is landfilled every year in the USA varies between 3 and 5 million tons (Jody et al., 1994; Jody and Daniels, 1999). In addition to automobiles, the residue produced by a shredder may also contain non-recyclable waste from household appliances, industrial equipment, railway freight cars, etc.

**Figure 3** Comparison of products that enter the recovery infrastructure

![Diagram showing percentage of products entering the recovery infrastructure](image)

Source: EPA (2006)

Figure 4 shows the material flow within the automobile recycling infrastructure. It should be noted that monetary flow is nearly always opposite to the material flow; the principal exception being the case of ASR where the landfill operator receives a tipping fee to take the ASR. After the end of a vehicle's useful life, the EOUP ends up with the dismantlers. However, due to capacity constraints of the dismantlers, close to 15% of the EOUPs end-up with the shredder (Duranceau and Lindell, 1999). The amount paid by the
A dismantler removes subassemblies such as the engine, transmission, radiator, catalytic converter, gasoline, fuel tanks, fluids, tyres, batteries, and air bags from the vehicle for their value or because the shredder requires their removal (Staudinger et al., 2001). The amount of non-metallic material content recovered by dismantlers is estimated to be very small, as the majority of the subassemblies are metal-based. After removal of the subassemblies, the hulk (i.e., the remains of the EOUP after dismantling) is sent to a shredder. The dismantler bears the cost of transportation of the hulk – about $15 per ton for an average distance of 160 km (APC, 1994). A shredder buys the hulk from a dismantler purely for its material content. Hulk purchase price depends on the mass of the hulk; however, typical reported values vary between $50 and $100 (Staudinger et al., 2001). It is estimated that there are between 180 and 200 shredders in the USA (Curlee et al., 1994; Das et al., 1997) and most shredders can handle 400–500 hulks per day.

As noted previously, a shredder receives a variety of EOUPs in addition to hulks. These EOUPs form the input stream to the shredding machine. The shredding machine chops the EOUPs into fist-sized pieces, which are separated into different output streams using various separation technologies (e.g., magnetic separators). As shown in Figure 4, the three main output streams of the shredding process are the ferrous metal stream, heavy blend stream (non-ferrous metals), and Shredder Residue (SR) stream. The ferrous metal recovered by the shredder is sold to steelmaking producers at a price of about $150 per metric ton, the non-ferrous metal is sold to a non-ferrous operator at a price of about $600 per metric ton, and the SR (ASR is the portion of the SR associated with vehicles) is landfilled in an EPA subtitle D landfill (Das et al., 1999). The cost of landfill depends on the density of the SR, the landfill price per unit volume, and the geographic
region. For an average ASR density of about 350 kg/m3, these fees correspond to
disposal rates in the range of $45–$75 per metric ton (Staudinger et al., 2001). The cost
of disposal of hazardous materials is higher, in the range of $75–$130 per metric ton.

A non-ferrous operator receives the non-ferrous metallic stream from the shredder
and separates it into streams such as aluminium, copper, and zinc. The sale of these
non-ferrous streams to secondary material producers is the source of revenue for
a non-ferrous operator, whereas purchasing feedstock material and landfill tipping fees
constitute a large fraction of their costs. A typical non-ferrous operator (there are about
40 in the USA) has a capacity of 25 metric tons/h and operating costs in the range of
$80–$100 per metric ton (Das et al., 1999). The amount of solid waste produced
at vehicle end-of-life is estimated to be about 325 kg, of which about 300 kg is ASR.

2.2 Historical perspective on automotive recovery infrastructure

The infrastructure for the recycling of vehicles, in terms of such issues as the
technologies used to recover components and recycle materials, and the relevant business
entities (e.g., dismantler and shredder), is largely the same in the USA, Europe and Japan.
However, the principal motivators for the infrastructure are different. In the USA the
vehicle recycling infrastructure is largely profit-driven, while in Europe and Japan
regulatory and legislated policies as well as a lack of landfill space (Field et al., 1994;
Kurasaka, 1996; Kanari et al., 2003) appear to be the dominant factors. Mandatory
recycling policies in Europe and Japan and concomitant fees have been designed to
ensure the continuing existence of recovery/recycling infrastructure and achieve
mandated material recovery objectives. In spite of the differences in the recycling
infrastructures around the globe, they have all benefited from a number of factors.

a The material composition of a vehicle that enters the recycling infrastructure today
is rich in ferrous content. A large market for scrap ferrous material makes recycling
of ferrous-intensive automobiles a very profitable business.

b The availability of high-speed mechanical shredding machines has reduced the
cost of breaking down an end-of-use vehicle into small pieces, thus improving the
profitability of shredders. Given the interconnected nature of the entities within
the infrastructure, a reduction in cost for the shredder serves to benefit the entire
recycling chain.

c The wide use of efficient technologies for the separation of materials types
(e.g., magnetic separators) to drastically reduce manual sorting.

d The adoption of steelmaking process technologies that can accommodate high levels
of ferrous scrap as material input, thus serving to stimulate demand for scrap content.

Though it is easy to understand how factors (a)–(c) affect the profitability of the recycling
infrastructure, some discussion of the fourth factor is needed.

Before the Basic Oxygen Furnace (BOF) began to be adopted by the steelmaking
industry in the late 1950s, the Basic Open Hearth (BOH) Furnace was widely used
producing 90% of the total steel in the USA) (Fruehan, 1998). The motivations of
transiting from BOH to BOF technology were the energy and cost savings.
The introduction of the BOF technology in the USA led to a decrease in the market
demand for steel scrap as BOF could only accommodate 30% scrap in its feedstock as
opposed to 50% possible with the BOH process (Chandler, 1986; Field et al., 1994; Graedel and Allenby, 1995). Thus, junkyards (or dismantlers, as they are called today) recycled only the most valuable components and often abandoned the rest of the vehicle to an auto graveyard (Field and Clark, 1991). In short, the introduction of the BOF technology resulted in the 1970s 'junk car' problem.

To solve this problem many suggested legislative solutions, but ultimately, no legislation was enacted to address this situation. Only with the adoption of the Electric Arc Furnace (EAF) steelmaking process and the development of the shredding machine was the junk car problem eliminated. The EAF transformed junk cars into a material resource since the EAF steelmaking process could use as much as 100% scrap for its charge to produce steel (Graedel and Allenby, 1995; Fruehan, 1998). The shredding machine coupled with efficient separation technologies provided scrap ferrous content from EOUP vehicles at a low price. Other benefits of using an EAF were that it could be run on a relatively small scale with low capital cost.

There are two important lessons to be learned from this past experience. First, a seemingly beneficial technology from the perspective of one life cycle stage can adversely affect the other stages of the life cycle. For example, in the above case, the change from BOH to BOF technology improved the efficiency of the steelmaking process; however, it produced a negative effect on the automotive recycling infrastructure. This suggests that care is needed when introducing significant changes within a complex system such as the automotive value chain to ensure that positive benefits achieved in one stage of the life cycle are not eroded by adverse effects within other life cycle stages. Second, deleterious life cycle impacts can be reduced if the true root cause for the adverse effects is understood. For example, recognising that the junk car problem of the 1970s was due to the limited ability of the BOF process to accommodate scrap could have caused systems-thinkers to promote the early adoption of EAF technology by the steelmaking industry. One could argue that in this case, an inadequate understanding of the situation led to an unsustainable approach focused on treating the symptom – creating large auto graveyards in the USA.

3 Assessment of automotive recycling infrastructure research

For nearly two decades, researchers have worked to understand the automotive recycling infrastructure, describing the material flows and economic exchanges within the infrastructure, and the impact of vehicle changes on it. In the following section, a brief description of key research findings that have contributed to an understanding of the infrastructure is provided, and gaps in the current knowledge are identified. Many of the contributions are focused on modelling strategies have been applied to characterise the recovery infrastructure including material flow analysis and life cycle assessment; limitations of these strategies are also discussed.

3.1 Research overview

Dieffenbach et al. (1993) focused on describing the automotive recovery infrastructure using Technical Cost Modelling (TCM). The total cost associated with each business entity was calculated as a function of various factors such as material processed, tooling, maintenance, and labour. Though TCM is effective in determining the costs and revenue
associated with a manufacturing facility, it is not well-suited for material flow analysis within a facility. Using the TCM approach, Dieffenbach et al. (1993) modelled the costs associated with recycling and the impact of plastics recovery under certain scenarios based upon vehicle buying/selling costs, material and hulk costs, and transportation and landfill costs. However, the study did not address changing automotive recycling costs associated with changing material composition of vehicles.

Field and Clark (1994) conducted a study to understand the impact of various recycling policies on the automotive recovery infrastructure. They focused on establishing an economic framework for analysis of existing and new recycling technologies, and analysing potential policies directed towards increasing recycling rates. The study was a comparative analysis, and did not provide absolute numbers on the level of impact.

Life Cycle Analysis (LCA) techniques were employed by Das et al. (1997) to study the impact of changing automotive material composition on energy consumption and waste generated. Though LCA is effective in developing material inventories and assessing the impact on each stage of a product life cycle and is particularly suitable for comparative analysis of different alternatives, it does not provide an absolute impact for each alternative. The aim of the study conducted by Das et al. (1997) was to determine the impact of new separation technologies (particularly plastics) on energy consumption. Waste reduction was found to be significant if all thermoplastics were recycled and the remaining ASR incinerated. The effectiveness of this approach in reducing the amount of waste was almost completely due to waste incineration.

In another LCA, the energy consumption of Electric Vehicles (EVs) was compared to conventional internal combustion engine vehicles (ICVs). It was reported that EVs consumed 24% less energy over their life compared to ICVs (Sullivan and Hu, 1995). However, a reduction in vehicle weight and greater use of recycled materials was shown to have a much more positive impact on the life cycle energy consumption of an ICV than the change to an EV.

A report published by the Energy Division at Oak Ridge National Laboratory examined the possible changes in the material composition of future vehicles, and identified life cycle problems associated with vehicle weight reduction through the use of alternative materials (Das et al., 1997). This work was continued by Das and Curlee (1999) who studied the impact of material substitution (aluminium and composites) on the profitability of the recycling infrastructure. An extensive analysis was conducted with respect to the changing degree of material substitution and the change in the cost structure of the recovery infrastructure. However, the model was highly aggregated with respect to the operations of the dismantler.

In another study, a Vehicle End-Of-Life (VEOL) model (Bustani et al., 1998; Cobas-Flores et al., 1998) was developed to evaluate the material/parts flows and economic exchanges within the automotive industry material life cycle. The questions that were addressed in study were

- What will be the effect of increased plastics recovery?
- What will be the impact of a decrease in vehicle sales?
- What will happen if the body of the vehicle is made of aluminium, plastics, or ultra-light weight steel?
An optimisation model using a goal programming approach was developed by Isaacs and Gupta (1997) to study how polymer-intensive vehicles could impact the automotive recovery infrastructure. The goal of the study was to determine the optimum level of plastics removal prior to the shredding operation so as to maintain the profitability of all business entities within the recovery infrastructure. Using the same goal programming approach, two additional studies were conducted, one to determine the impact of aluminium-intensive vehicles on the recovery infrastructure (Boon et al., 2000) and another to compare the impact of EVs, hybrid-electric vehicles and polymer-intensive vehicles on the recovery infrastructure (Boon et al., 2003). Optimisation is an ideal approach to make the best decision for a given scenario, but the approach requires accurate mathematical descriptions of constraints and objectives.

In another optimisation-oriented study, Johnson and Wang (2002) analysed the current European Union legislative policy on the management of EOUPs. The aim was to determine the optimum recovery option under the constraint of meeting a recovery rate of 95% by 2015. The two options studied were manual disassembly to remove a certain level of polymers before shredding, and the amount of the vehicle to be shredded. Zamudio (1996) developed a dynamic model of the automotive recycling using a system dynamics approach. The model did not account for the materials associated with the replacement of parts and mandatory dismantling or its economics. The model assumed that material flows are interdependent, so the flows of different materials (e.g., steel and aluminium) were never analysed or characterised separately. It was concluded that the existing recycling infrastructure would have to be modified in order to survive changes in the recovery market.

Several other models utilised system dynamics to characterise the material flow and economic exchange within the recovery infrastructure. In one study, Bandivadekar et al. (2002, 2004) developed a simulation model of the recovery infrastructure to understand the impact of changing material composition on the economic and environmental sustainability of the infrastructure. The model described the material flow and economic exchange for each business entity within the recovery infrastructure. The model was then used to determine the profitability of each business entity under material and market uncertainties. In another system dynamics-based study, the strategies that may be employed to meet the EU ELV material recovery targets were analysed (Ferrao et al., 2006; Ferrao and Amaral, 2006; Amaral et al., 2006). In another study, Kumar and Sutherland (2007) investigated various technological strategies that may be required to improve the material recovery efficiency of the automotive recycling infrastructure. Based in their analysis, it was determined that the technological burden will have to be shared by both the dismantlers and shredders to achieve a recovery target comparable to that being mandated in Europe.

3.2 Limitations and knowledge gaps

Each research effort described previously has been undertaken to characterise either material flow or economic exchange associated with the automotive material life cycle. Some efforts have characterised both together to understand the impact of several scenarios on the automotive recovery infrastructure. However, some of the efforts have one or more shortcomings (or limitations). These limitations provide some insight into research issues that need investigation. Furthermore, given the totality of all the work that
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has been conducted, there exist gaps within the knowledge base; these gaps suggest research questions that merit study.

One limitation of the models that have been developed for the automotive recovery infrastructure is that they do not adequately describe the complex material flows and economic transactions within the infrastructure. For example, as stated previously, dismantlers are mainly concerned about selling quality subassemblies, parts, or components. For their business, the material composition of the subassemblies, parts, or components does not affect the profitability as long as the customer is satisfied with the quality of a used component. Most of the models developed by researchers have assumed that the dismantlers remove a certain material fraction and sell it at a price ($/kg) proportional to the scrap price. Although, these models describe many aspects of the recovery infrastructure, the impact of vehicle material changes on the dismantling business as predicted by these models may or may not provide results consistent with future behavior. Another example is the handling of the small fraction of vehicles that are sent directly to the shredder. Virtually none of the models address what happens to components such as fuel tank, catalytic converter, and tires that regulations mandate the shredder to remove. Thus, research is needed to enhance existing models to address these limitations and better describe the complexity of the automotive recovery infrastructure.

A second limitation is related to the market forces that affect the recovery infrastructure. Most models either do not consider market factors such as demand for a particular subassembly or ferrous scrap prices, or assume them to be exogenous variables to the infrastructure. Exogenous variables are those that are external to the model and are therefore not dependent on the model parameters, and do not change as parameters change; on the other hand, endogenous variables are part of the model, and may be a function of other model parameters. For the case of the model, exogenous variables usually are assigned fixed values for a given scenario that is being studied. This represents a deficiency in the models, since in some cases it may be more appropriate to introduce these variables via functional relationships (i.e., consider them to be endogenous variables). For example, it may be important to incorporate a functional relationship for the demand associated with a particular subassembly into the model rather than considering the demand to be constant via an exogenous variable. To summarise, therefore, research is needed to develop infrastructure models that incorporate market factors.

This discussion on the interaction of market forces with the recovery infrastructure suggests a third limitation that has been previously identified: lack of consideration for government interactions with the infrastructure. The effect of government policies has not been sufficiently considered in previous analyses. One question that must be answered in order to understand this limitation is: why is it important to study policy impacts on the recovery infrastructure? Recall the discussion on the historical perspective on automotive recovery infrastructure. It was mentioned that even though the automotive recovery infrastructure is profitable in Europe and Japan, government initiatives such as the ELV directive are causing designers to think about automotive recovery during the design stage. In the USA, though no such ELV policy currently exists, in the future the recovery infrastructure or the OEMs may face a similar policy (or policies). Thus, to ensure the economic and environmental sustainability of the recovery infrastructure it is important to study the impact of potential policies that may be enacted by the government. Primarily, work that has examined the effect of future scenarios on the recovery infrastructure emphasis has largely been placed on changes in vehicle material
composition or powertrain technology modifications. Among the research contributions that has considered policy impacts on the infrastructure is the recent work at the Technical University of Lisbon (Ferrao et al., 2006; Ferrao and Amaral, 2006; Amaral et al., 2006); they have conducted analyses to identify the recycling technology innovations required to maintain the sustainability of the infrastructure under the various European Union directives. Beyond this work, very few studies have examined the potential technological changes that the recovery infrastructure may undergo in the coming years. Clearly, much additional research is needed to provide a link between potential future government policies and the economic and environmental sustainability of the automotive recovery infrastructure.

A final limitation related to the work that has been done to characterise the recovery infrastructure is the limited variety of future scenarios that has been considered in examining infrastructure impacts. Most researchers have restricted their attention to vehicle material composition or powertrain technology changes in developing future scenarios. Other variables that have not been adequately addressed in developing future scenarios include: market shares of new vehicles, recycling/recovery technologies, and government policies directed at improving recovery rates. Research is needed that considers a broader spectrum of possible future scenarios and their combined impact on the recovery infrastructure. In the next section, some of the possible scenarios that should be included in the analysis will be discussed.

In addition to the limitations identified above, there are several other questions that have not been studied in the past. In order words, there are several gaps in the existing body of knowledge. Some of these open questions include:

- What is the impact of recycling vehicles in terms of energy consumed over the life cycle? What is the energy consumption of the recycling infrastructure itself? Will the energy consumption of the recycling infrastructure change when the next generation of vehicles are processed?

- To what extent is the material loop closed by the vehicle recycling infrastructure? For example, is the aluminium reclaimed by the shredder effectively utilised by the automotive industry? Or, is it down-cycled for use in other applications?

- In the work that has been discussed, changes in material composition are used to describe the evolution of the vehicles introduced by the automotive industry. Is this approach sufficient to describe what will happen? Are other approaches needed to describe how the infrastructure will behave as the number and distribution of vehicle types (e.g., hybrids and trucks) changes?

- Will the variation in terms of geographic region affect the sustainability of the infrastructure?

It is believed that these questions are important to address to not only ensure the sustainability of the recovery infrastructure, but also to help industry understand the impact of their design decisions across a wide range of sustainability metrics. Apart from the research needs identified in this section, additional research questions will be provided in the next section.
4 Future challenges for the automotive recovery infrastructure

A discussion of the future challenges to be faced by the automotive recycling infrastructure should begin by identifying some of the fundamental trends and future directions of the automotive industry itself. These trends include efforts to reduce vehicle weight and reduce emissions. With respect to vehicle weight reduction, it must be recognised that the automotive industry utilises a tremendous amount of material resources. Table 1 lists the fraction of the total annual US consumption that is used by the automotive industry. As is evident from the table, the automotive industry is the primary consumer of materials such as lead and rubber. It is also a significant consumer of aluminium, zinc, and ferrous materials. Since two-thirds of fuel consumption is attributable to vehicle weight (An and Santini, 2004; Lovins, 2005), OEMs use of lighter materials such as aluminium, magnesium, plastics, and polymer composites is in response to calls for improved fuel economy, e.g., USA CAFE requirements. Currently, the CAFE requirement is 27.5 mpg for passenger cars, and 20.7 mpg for light trucks (Brown, 2002). Thus, the desire for improved fuel economy explains why the relative use of ferrous materials has dropped significantly since the 1970s. Figure 5 shows how the vehicle material composition has evolved over the last 30 years. As is evident, the ferrous fraction currently makes up nearly two-thirds of the total vehicle weight as opposed to approximately 75% in the past. This decline in the figure over the last several decades can be largely attributed to the use of lighter materials such as aluminium, plastics, and composites (Ward’s Communications, 2006).

In 1993, the US government and the automotive industry established the Partnership for a New Generation of Vehicles (PNGV). The PNGV set a target that called for a reduction of 40% in vehicle weight within ten years (Table 2) (NRC, 2001) through component redesign and/or the use of lighter-weight materials. More recently, the automotive industry has investigated alternative fuels and power sources for reducing the environmental impact of the vehicles, e.g., hybrid vehicles, fuel cell technologies, and biofuels (Beer, 2000; Dearing, 2000; Lave et al., 2000; Greene et al., 2004; Ogden et al., 2004; Estudillo et al., 2005). The 2010 concept cars are all lightweight vehicles that use either an alternative fuel or some other non-traditional power source. It is expected that this new generation of vehicles will have about 30-60% of the market share by 2030 (Das et al., 1997).

<table>
<thead>
<tr>
<th>Material</th>
<th>Percentage of total</th>
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<tr>
<td>Plastics</td>
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<tr>
<td>Aluminium</td>
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<td>Copper</td>
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<td>Steel</td>
<td>13.3</td>
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<tr>
<td>Rubber</td>
<td>72.6</td>
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</table>

Source: Adapted from Ward’s Communications (2006)
As part of the PNGV effort, definitions of aluminium- and Composite-Intensive Vehicles (CIVs) were established. Table 3 gives a comparison among the material composition of a 1995 generic vehicle (Sullivan et al., 1998) and two concept cars (Dhingra et al., 2000) that are rich in aluminium and composite material. As can be seen from the table, one of the concept cars contains more aluminium than ferrous material, thus, the term ‘aluminium-intensive’. In the other concept car, plastics is the largest material and thus the term ‘composite-intensive’. In fact, Ng et al. (1999) defined that an aluminium-intensive vehicle is one in which the major components are made of aluminium and the total mass of aluminium exceeds ~315 kg. For CIV, the amount of plastics should be more than ~230 kg. In should be noted that these light-weight materials are chosen due to the suitability of their mechanical and chemical properties to the automotive industry. A brief description of the advantages and disadvantages of these materials is provided in the next section. In addition, the benefit of substituting these materials in place of ferrous material with respect to energy consumption, emissions and waste generated across the vehicle life cycle will also be provided.

Another partnership, the FreedomCAR and Fuel Partnership, was established between the US government, the automotive industry and the energy companies, in 2003 (DOE, 2004; USCAR, 2006). The long-term goal of the partnership is a future with clean and sustainable transportation that is available to everyone. To achieve these goals, the partners have identified a number of promising technologies such as fuel cell, electric propulsion, and lightweight materials, and are supporting research to address the issues.
related to the development of such technologies and the support infrastructure. Specific technological targets for the years 2010 and 2015 are summarised in USCAR (2006) and DOE (2004). In addition to the FreedomCAR and Fuel Partnership, the USA DOE has also established a new Cooperative Research and Development Agreement (CRADA) to facilitate research in recycling technologies for current and future post-use vehicles (Daniels et al., 2004). The partnership among Argonne National Laboratory, the Vehicle Recycling Partnership (part of US Council for Automotive Research), and the American Plastics Council focuses on developing technologies for recovery of plastics from SR.

Table 3  Comparison of 1995 generic vehicle and future vehicle material composition

<table>
<thead>
<tr>
<th>Material</th>
<th>1995 vehicle</th>
<th>Aluminium-intensive</th>
<th>Composite-intensive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrous</td>
<td>985</td>
<td>222</td>
<td>239</td>
</tr>
<tr>
<td>Aluminium</td>
<td>97</td>
<td>332</td>
<td>204</td>
</tr>
<tr>
<td>Other non-ferrous</td>
<td>41</td>
<td>44</td>
<td>73</td>
</tr>
<tr>
<td>Plastics</td>
<td>143</td>
<td>114</td>
<td>247</td>
</tr>
<tr>
<td>Other</td>
<td>192</td>
<td>199</td>
<td>201</td>
</tr>
</tbody>
</table>

*Source: Adapted from Sullivan et al. (1998) and Dhirgra et al. (2000)*

4.1 Material changes

There are several benefits to using lighter weight materials during the life cycle of a vehicle; however, the impact that these lightweight vehicles, as their market share increases, on the recovery infrastructure is unknown. Since the existing automotive recovery infrastructure is well suited to ferrous-based vehicles, using lighter weight materials may have a negative impact on the environmental and economic sustainability of the recovery infrastructure. In other words, as these material changes are instituted, the percent of waste generated, i.e., the ASR, is most likely to increase, and the profitability of each business entity in the recovery infrastructure is likely to decrease. As stated previously, profitability is the major motivation for business entities engaged in the USA automotive recovery infrastructure. Though no ELV directive (ELV, 2000) or regulation exists in the USA at present, it is believed that the recovery infrastructure may have to improve recovery rates in the future.

4.1.1 Aluminium

The use of aluminium in automotive components is on the rise as it offers a substantial vehicle weight reduction potential when compared with ferrous materials leading to improved fuel economy and decreased engine emissions. Aluminium offers a number of benefits relative to ferrous materials:

- more abundant in the earth’s crust (third after oxygen and silicon)
- better ductility, malleability, and corrosion resistance
- improved conductor of electricity.

For automotive applications, the lower density and recyclability of aluminium also provides incentives to the OEMs to increase the use of aluminium in vehicles
(Plunkert, 2005). The density of aluminium is approximately one-third that of iron and steel. Thus, for identical part geometries, an aluminium component will have one-third the weight of a steel component. For parts with the same or better stiffness/crashworthiness, Gesing and Wolanski (2001) report a weight saving potential of up to 55% for aluminium. Apart from weight savings and recyclability, aluminium components can be designed to meet the torsion and stiffness requirements of the automotive industry (Kelkar et al., 2001).

The virgin processing of aluminium uses ten times more energy than steel, however, several life cycle comparisons have revealed that substituting aluminium for conventional steel in a vehicle will consume less energy over the entire life cycle (Sullivan and Hu, 1995; Saur et al., 1995). These studies show that the use of aluminium to increase vehicle fuel economy offsets the increased energy requirements for virgin aluminium processing. The studies also conclude that the potential energy saving will be higher if aluminium is recycled back into automotive applications. In another LCA, it was found that the energy saving potential for the entire US fleet will be 4.6% by 2030 if mass commercialisation of aluminium-intensive vehicles is achieved by 2005 (Stodolsky et al., 1995). A comparison for a body-in-white autobody application among aluminium, conventional steel, and ultralight steel showed that aluminium offers the highest energy and CO₂ emissions savings potential (Das, 2000).

In addition to the high energy consumed during aluminium processing, the price of virgin aluminium, which can be five times higher than steel, is another major factor that inhibits the widespread use of aluminium in the automotive industry. However, the potential weight and fuel savings as well as improved autobody resistance to corrosion, which enhances the vehicle life/value, may offset any price increase associated with the use of primary aluminium. Aluminium’s high scrap price is another factor that offsets the high initial cost of aluminium and favours its use as a substitute for steel in vehicles (Phillips, 1996).

4.1.2 Composite material

A low cost of production is one of the principal advantages of polymer composite or plastic components relative to aluminium and iron in automotive applications. In addition, the moldability of composites makes them an attractive design alternative to reduce wind noise and vehicle air drag. It is easier to mould a better aerodynamic vehicle shape using composites than steel or aluminium (Choi et al., 2001). Other benefits of using composites are excellent corrosion resistance, high specific strength, energy absorption characteristics, crashworthiness, and part consolidation opportunities (Brylawski and Lovins, 1996, 1999; Brylawski, 1999).

Ecobalance (2001) performed a LCA to assess the difference in global warming potential, total energy consumption, gaseous emissions, and total solid waste when the plastic material content is increased in a vehicle. Two interrelated factors, weight reduction and effect of vehicle mass on fuel consumption, were used to develop two scenarios. For the first scenario, it was assumed that the weight is reduced by one-half by replacing ‘original parts’ with ‘plastic parts’ and that 50% of the fuel consumed by the vehicle is due to its mass (the balance is attributed to friction). In the second scenario, the weight is reduced by one-third and 66% of the fuel consumed is due to vehicle mass. It was found that except for SO₂, particulate matter, and total solid waste, the substitutions under both scenarios had a positive effect on the
other assessment categories. In addition, the total life cycle saving in terms of CO₂ equivalent for the two scenarios was determined to be 1.6 and 5.8 metric tons, and the total fuel savings was found to be 830 and 3200 litres. Similar results were reported in several other life cycle studies of CIVs (Dhingra et al., 1999, 2000; Das et al., 2000; Schexnayder et al., 2001).

4.2 New powertrain technologies

As stated previously, several new powertrain technologies are being investigated to improve the fuel economy of a vehicle and meet the tail-pipe emissions standards during the use phase of a vehicle. These include Compression Ignition, Direct Injection (CIDI) diesel engines, electric vehicles, hybrid vehicles, fuel cell technologies, biofuels, Compressed Natural Gas (CNG), and gas turbines. Although several of these powertrain technologies are still in the concept stage, the benefits of using these new powertrain technologies during the use phase are well documented, and research is progressing to realise the benefits. Table 4 summarises the benefits of some of these technologies. As is evident from the table, the documented benefits focus on the environmental impact of these new powertrain technologies during the use phase of the vehicle. Also indicated in the table are researchers who are exploring the economics of new powertrain technologies. However, the impact of these powertrain technologies on the automotive recycling infrastructure is still unknown.

Table 4  Summary of past research related to new powertrain technologies

<table>
<thead>
<tr>
<th>Reference</th>
<th>Research summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lave et al. (2000)</td>
<td>Emissions from seven new powertrain technologies</td>
</tr>
<tr>
<td>Beer (2000)</td>
<td>Emissions from hybrid electric vehicles</td>
</tr>
<tr>
<td>Ogden et al. (2004)</td>
<td>Life cycle cost of alternative fuels/powertrain vehicles</td>
</tr>
<tr>
<td>Greene et al. (2004)</td>
<td>Future market potential of diesel and hybrid powertrain vehicles</td>
</tr>
<tr>
<td>EPA (2005)</td>
<td>Future cost comparison of gasoline, diesel and hybrid-electric vehicles</td>
</tr>
</tbody>
</table>

4.3 Research challenges

As is evident from the above discussion, replacing steel with aluminium or composites will not only increase the fuel economy but also reduce the overall life cycle emissions and energy consumption. However, it is also likely that the total solid waste, which is usually landfilled in the USA, will increase with such material substitutions. It is largely unknown what effect such substitutions will have on the generation of solid waste (ASR disposed to landfills) and thus, the environmental sustainability of the recovery infrastructure (Daniels et al., 2004). New powertrain concepts such as fuel cells also offer tremendous environmental advantages during the use phase of the vehicle; however, their impact on the recycling infrastructure is again unknown. Thus, vehicular changes in the material composition towards lighter materials (e.g., plastics, aluminium, ultra light high-strength steels, and composites) and powertrain technologies (e.g., hybrid and electric) will continue to put pressure on the EOUP recycling infrastructure (DOE, 2001).
In order to understand the impact of the vehicular changes in the material composition and powertrain technologies on the EOU recycle infrastructure, one of the research challenge is to undertake a comprehensive analysis focused on developing scenarios for vehicles of the future and analysing the impact of these scenarios on the environmental and economic sustainability of the recovery infrastructure. In addition, the analysis should also consider scenarios that embrace improved recovery technologies, markets for components/materials that are currently not being recovered, and markets for components associated with new powertrain technologies. The short-term impact in terms of the profitability of each business entity and long-term impact in terms of the waste that is generated by the recycling infrastructure should be at the core of any research that is undertaken in this area.

Another research challenge is to develop new recycling and recovery technologies for the automotive industry of the future. Also required are strategies to introduce such technologies into the infrastructure and educate business entities on their use. These technologies must be demonstrated to have a positive effect on the economics of the infrastructure; otherwise they will not be implemented. The effectiveness of these technologies in improving the recovery rates will also determine whether the technologies are adopted by the infrastructure. These new recycling and recovery technologies should be treated as additional scenario variables in assessing the performance of the infrastructure to the vehicle changes discussed above.

Yet another research challenge is the investigation of the impact of potential government policies (similar to the policies being enacted in Europe and Japan) on the future of the recovery infrastructure. As examples, studies in this area could

- demonstrate the potential negative consequences of a poorly formulated policy on the economics and environmental sustainability of the recovery infrastructure, or
- examine the effect of policies such as the EU ELV Directive on the profitability and landfilled ASR for a wide range of future vehicle scenarios.

While most often in the USA, market-based forces are preferred as opposed to government intervention, such intervention may be necessary to avoid a repeat of the 1970s ‘junk’ car problem. Of course, simulation represents an excellent method by which the efficacy of such intervention can be assessed.

5 Summary and conclusions

As is evident from the discussion in this paper, replacing steel with aluminium or a composite material not only increases the fuel economy but also reduces the overall life cycle emissions and energy consumption. However, it is also likely that the total solid waste, which is usually landfilled in the USA, will increase with such material substitutions. It is largely unknown what effect such substitutions will have on the generation of solid waste (ASR disposed to landfills) and thus, the environmental sustainability of the recovery infrastructure. In order to understand the possible impact of such vehicular changes, the history of automotive recovery infrastructure along with its current status with respect to the material flows and economic exchanges was presented. The following key points have been made by this paper:
• in the past, the automotive recovery infrastructure has faced similar challenges to those it faces today in terms of vehicle changes and government regulations

• improved models are required to better characterise the interaction among the various stakeholders in the automotive recovery infrastructure

• in addition to the development of improved models, several questions, e.g., energy issues, life cycle CO2 emissions, effect of light-weight materials, and impact of new powertrain technologies should be examined via scenarios that are required to better understand the new challenges.

References


Ward’s Communications (2006) Ward’s Motor Vehicle Facts and Figure, Southfield, MI.
