Automobile Recycling Policy: Findings and Recommendations

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Prepared for the Automotive Industry Board of Governors,
World Economic Forum

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Davos, Switzerland — February 1994

Contents

Recycling of the Automobile: Policy Options and Recommendations

Preface

In 1993 the Automotive Board of Governors of the World Economic Forum decided to undertake a cooperative activity focusing on the social impacts of automobiles. Two initial projects were approved — the first to develop recommendations for recycling and the second to develop a research agenda for mobility. The MIT International Motor Vehicle Program was asked to undertake these projects and report back to the Automotive Governors at their meeting in 1994.

This report focuses on recycling. As an objective neutral party, MIT has compiled a knowledge base that examines the many complex issues relating to recycling. Although this report was prepared at the request of the Automotive board of Governors, it was not prepared solely as an industry response document. Rather, it attempts to focus on the concerted actions that both industry and government should take. MIT hopes that the document can serve as the basis for forging international consensus on a rational approach to recycling policy.

This document presents the findings and recommendations of this group to the Board of Governors. In addition to these recommendations, supporting materials in the form of four appendices, tracing specific aspects of the problem of vehicle recycling and the ways in which these problems can be analyzed, are appended.

The first appendix summarizes the global status of automobile recycling today and provides a detailed economic framework and analysis of both the existing recycling infrastructure and potential new recycling technologies. The second appendix presents a systematic framework for analyzing the economic structure of the automobile recycling infrastructure and discusses appropriate policy options based upon this analysis. The third appendix discusses the potential of an emerging analytical paradigm that can integrate consideration of the environmental, technological, and economic implications of product design, life cycle analysis. A framework based upon the principles of this paradigm will be required to resolve the conflicting elements of social goals as applied to economic products. The final appendix provides in great detail the evolution of the existing automobile recycling infrastructure in the United States, showing how economic forces and technological innovations led to its development. Further, it articulates the impact of vehicle lightweighting and materials substitution on vehicle recyclability.

Overview

Spurred by initiatives throughout the world, automobile recycling is receiving increasing attention. Specific legislative initiatives in Germany and Japan are being viewed as potential policy blueprints by legislators interested in mitigating environmental ills arising not only from the disposal of automobiles in particular, but consumer durables in general. Automobiles, white goods, consumer electronics, and computers are leading candidates for recycling, in addition to the more prevalent packaging initiatives.

These efforts are taking place against the backdrop of a rising set of environmental initiatives that can be grouped under the rubric of "sustainable development." Within this context, recycling is viewed not only as a mechanism for reducing environmental impact by reducing the amount of waste released to the environment, but also as a mechanism for reducing consumption of resources in general by reusing materials already extracted from the environment rather than relying upon virgin materials. This duality has served to make recycling a central aspect of many environmental programs.

However, recycling is an industrial process too, relying upon and constrained by established technologies, consuming resources, capital, and manpower, and producing waste. Furthermore, recycling faces unique market dynamics, given the availability of perfect substitutes in the form of established virgin materials. As a consequence, recycling industries are delicate creatures, perpetually walking a fine line between technological feasibility, economic constraints, and market demands. There are numerous examples that demonstrate this delicacy, as well as the perverse consequences of well-intentioned efforts to promote the collection and use of recyclables.

Beyond the fragility of these industries is the fact that, because of the vagaries of local markets, the relative efficacy of recycling can be dominated by regional considerations. The costs of disposal, processing, and virgin materials vary across regions, and these differences determine the economic appropriateness of recycling. As a consequence, recycling requirements imposed in one region, where they may be economically valid, have the potential to limit markets to those suppliers facing similar economic conditions while excluding suppliers whose economies cannot support the development and implementation of the necessary technologies.

The complexity of recycling places considerable burdens on policymakers wishing to influence the scope and nature of the industry. Because present recycling activities are a reflection of the existence of an economic opportunity rather than a response to a technological or environmental necessity, efforts to influence recycling must act carefully to preserve the balance between the demand for recyclables and the economics of the recycling industries. Inadequate consideration of this tension can lead to perverse consequences, where initiatives designed to increase recycling and reduce environmental damage may result in opposite effects.

Current Status Of Automobile Recycling

At the root of the question is the issue of recyclability. Although widely discussed, there is considerable confusion about its meaning. Recyclability is a characteristic that has both technological and economic implications. On the technological side, recyclability requires the existence of methods that can be used to extract the constituent materials from an obsolete product. On the economic side, recyclability depends upon the existence of a market for these extracts. Furthermore, there must be a balance between the cost of employing the extraction technology and the quality of the extract such that the recycler has an economic incentive to undertake the recycling.

The problem of automobile recycling today reflects the nature of recyclability. With the downsizing of the automobile, the metallic fraction of the automobile has reduced overall, and the ferrous fraction within that has also reduced. While there currently is a ready market for the ferrous and non-ferrous metallic fractions, there is no demand for the other elements (largely polymers, fabrics, and glass) in the form that they emerge from the shredder. Instead, they are disposed of, usually in landfills. However, the contribution of this “automobile shredder residue” (ASR) to overall landfill burden is relatively small, rarely larger than 2%. If landfill costs are low, the costs of the disposal of this ASR is a small fraction of the cost of operating a shredder. However, if the costs of landfill are high, the shredder may not be able to cover his costs, since there are other competing sources of ferrous scrap.

Although many observers have pointed to the rising polymeric content of the automobile as the primary culprit in the decreasing recyclability of the automobile, the problem is far more complex than the automakers’ decision to employ any particular class of materials. The automobile recycling infrastructure today is composed of several competing economic agents in addition to the automaker, each with his own set of technological and economic constraints.

A complex web of market and technological interactions is currently in place to recycle and dispose of the de-registered or end-of-life vehicle (ELV). Roughly 75% of the automobile by weight is recovered and returned to the used parts market or the secondary metals market today. Increasing the recycled fraction of the automobile will not only require the development and introduction of new materials extraction and processing techniques, but also the recognition that the existing infrastructure is an economic system of considerable complexity and flexibility. While the automaker’s choice of materials impacts this system on several levels, materials selection alone cannot accommodate all the needs of the recycling infrastructure and the needs of the automobile manufacturer. Resolution of this tension will require a system-wide perspective on the problems, both technical and economic, of vehicle production and use, material recovery, and waste disposal.

Policy Imperatives Underlying Recycling Initiatives

In light of the current status of automobile recycling, it may be difficult to understand the rationale behind current recycling initiatives. However, when viewed against the backdrop of sustainable development, several underlying themes emerge.

First is the very real interest in increasing the rate of recycling of the automobile. In spite of the fact that 75% of the vehicle is routinely recycled today, there are pressures arising both from the public and from governments to increase this percentage. This can be viewed as an extension of a rising concern about all consumer durables, but automobiles are the most visible members of this product class.

Ancillary to this policy initiative is the desire to raise the overall level of environmental performance within the existing automobile recycling infrastructure. There are any number of apocryphal tales of suspect behavior within the current industry. Recycling initiatives can also be viewed as initiatives directed toward improving practices within the existing infrastructure, particularly with respect to environmental performance.

Second is extended producer responsibility — the idea that the producer's environmental consciousness should extend beyond the factory walls and into a stewardship of the product throughout its lifecycle. This notion has many proponents, yet there is little knowledge of how it can be made operational within the confines of current economic and regulatory practices. Many of the current initiatives are efforts to develop such instruments.

Finally, there are considerations of product and industrial competitiveness. Environmental technology can be an important area of technological competitiveness, as the size of the markets for their environmental technologies demonstrates. Since much of this technology has been commercialized under the impetus of environmental strictures, recycling initiatives may represent a way to spur the development of new processing technologies. Alternatively, recycling initiatives can serve as a non-tariff trade barrier, restricting markets to those companies which have managed to develop products and technologies which accommodate local recycling imperatives.

This broad range of interests tends to reinforce the notion that recycling as a policy initiative is going to be a part of environmental policy for the foreseeable future. While some observers can easily demonstrate that the problem of automobile recycling is relatively small when compared with other solid waste issues and with other automobile environmental issues, recycling has become an important context within which these broader interests can be explored.

Findings

The automobile is one of the most completely recycled products in the world.

The highest consistent levels of automobile recycling have been in countries with a well-developed secondary materials recovery and reuse market and infrastructure. The automobile is actually one of the great success stories in the world of product recovery and recycling. As little as 25 years ago, the obsolete automobile was an economic and esthetic eyesore, accumulating in heaps throughout the world. However, by the mid-1970s, the automobile was referred to as one of the most recycled and recyclable of post-consumer products.

In terms of recyclability, roughly 75% of the car by weight is recovered and economically reused today. This statistic is particularly striking in two respects. First, this degree of material recovery is achieved wherever automobile recycling takes place. Second, no other product with such a large number of different materials is as highly recycled. Products which are more highly recyclable are composed of many fewer materials. For example, the aluminum beverage can is composed of two aluminum alloys (which can be mixed together) and one plastic resin coating (which can be burned without contaminating the aluminum).

However, it is the economic incentives behind recycling which have driven the development of this enterprise. Although the technology of recycling is roughly the same throughout the world, the most thorough recovery of automobiles takes place in regions where the markets for secondary materials and components are strongest and least encumbered. For example, it is estimated that well over 90% of the vehicles which are dropped from the vehicle registration rolls are actually recycled in the US (in comparison, roughly 80% of the aluminum beverage cans sold are recycled). This degree of recycling occurs in the absence of any requirement for disposal or penalty to the last user, or industry specific monitoring. Rather, it is driven by the fact that recycling of the automobile can be a very profitable business, provided the markets for recycled parts and materials operate freely.

(See Appendix D)

Public awareness of the recycling history of the automobile is poor.

The effectiveness of the existing modern automobile recycling infrastructure is not generally known among the public. Rather, the public has been traumatized by several specific images which have given the impression that automobile recycling is inadequately performed. For example, the case of automobile tires has been routinely presented as if the problems of their recycling and disposal were representative of the automobile as a whole. In fact, the problem of tire recycling is atypical of automobile recycling practice, reflecting the relatively low value placed upon the chemical commodities that can be produced from them (low grade fuel oils) and the historical aversion of the consumer market for remanufactured tires.

In this respect, the automobile is not unique. The public’s appreciation for environmental issues has frequently been at odds with that of environmental professionals, and the public’s memory in such cases is short. For example, many people are surprised to find that today’s automobile recycling issues echo concerns that were raised (and resolved) during the late 1960’s and early 1970’s.

Recycling is fundamentally an economic activity and, as a result, there are significant regional variations in the way recycling takes place.

Recycling is a historically evolved set of economic practices, reflecting national and regional preferences and materials polices. Recycling is a business activity, focused on profitably extracting economically valuable products from obsolete goods. Recycling is therefore dependent upon the composition of the obsolete product, the costs of acquiring obsolete goods, the costs of employing available extraction technologies, and the market value of the products extracted.

The view of recycling as an economic enterprise helps to explain why the business of recycling proceeds differently in different regions of the world. While the product (and therefore the recyclability of the product) may be the same, the economic and market conditions underlying the recycling enterprise will vary across regions. For example, US automobile recyclers face low landfill costs (roughly $35/ton) and a strong indigenous market demand for used parts and shredded steel scrap. Alternatively, German automobile recyclers face much higher landfill costs (starting at $100/ton) and much weaker local market demand for their products. These differences influence the profitability of recycling and therefore the interest of businesses to participate in the enterprise.

However, these differences are not a function of automaker action; rather, they reflect political attitudes about the value of landfill and economic attitudes about the value of secondary materials.

(See Appendices A & B)

Recyclability, a fundamental consequence of product design and technology, is the principal contribution of the automaker to the process of recycling.

The concept of recyclability is a much narrower notion than that of recycling. Recyclability is a consequence of the attributes of a product that contribute to the economic viability of its recycling. The greater a product's recyclability, the more economical the extraction of the valuable materials composing that product. The recyclability of the automobile is a strong function of the number and type of materials composing the vehicle and the ease with which they can be identified and isolated. These are attributes which depend upon the design of the automobile and the technologies available for secondary materials recovery.

The distinction between recycling and recyclability is a crucial one. Because recycling is an economic enterprise with many participants and differing economic objectives, the automaker cannot directly act to change the way in which vehicle recycling is undertaken. However, the recyclability of the automobile is directly under the control of the automaker, and is the aspect of the business of recycling where the automaker is best equipped to make a contribution.

(See Appendices A, B & D)

Acting to achieve additional environmental objectives should be done with great care so as not to disrupt the existing economic system. Both short- and long-term economic dislocations can result from such actions.

Secondary markets have been notoriously unstable and refractory to long-term policy interventions. The reasons for this behavior reflect the fact that secondary materials always face competition from a perfect substitute — primary (or virgin) materials. The existence of this competitor places an upper limit on secondary materials prices, limiting the ability of the secondary materials processor to redistribute the costs of policy actions directed at him. Ultimately, policy actions directed counter to prevailing economic conditions in the secondary market usually lead to the need for external supports to maintain the effected industries.

A classic example of the problems engendered by limiting the action of secondary materials markets is the problems faced by Sweden and Norway during the last automobile recycling crisis of the 1960's. Like much of the world, Norway and Sweden faced a rising tide of abandoned automobiles with the decline in the use of open hearth steelmaking (and thus the decline in scrap steel demand) and the rise in labor costs. However, the introduction of the heavy duty shredder and the rise of electric arc steelmaking did not eliminate their problems as they did elsewhere in the world. The primary reason for this situation was the fact that these governments, in order to protect their indigenous steel industry, forbade the export of steel scrap, lowering its value and reducing the profitability of the automobile recycling enterprise. These governments were forced to institute automobile deposit fees and recovery certificates to support their subsidy of the local steel industries.

(See Appendices A & D and their references)

Given the nature and success of existing recycling mechanisms, public policy should build upon and refine these elements, rather than attempting to create new institutions.

Highly interventionist, loop-closing policies, such as mandated recycled content or take back have had mixed successes. While there are many examples where recycling has been successful, mandated recycling has been less so. The recent German experience with their packaging programs has led to a serious restructuring of the institutions developed to carry out the principles of the 1986 Waste Management Act and a slowdown to the expansion of this effort to other product areas. The near financial ruin of the Duales System Deutschland GmbH (DSD) has been an object lesson in the economic risks inherent in imposing recycling requirements in the absence of strong market demand for recycled product.

However, the problems with the DSD are only one of the more recent examples of this principle. A more prosaic example can be found in community curbside recycling programs in the US. Here, communities have instituted programs for the collection of recyclables in the expectation that such materials would be absorbed by the existing recycling infrastructure. Instead, many such programs have overwhelmed these industries, leading not only to financial ruin of some but also to increased use of landfill space.

These examples point up the fact that recycling is a market driven activity. Because of this feature, public policy in this area should instead focus upon facilitating the actions of the market, rather than trying to direct the actions taking place within it. While businesses rely upon the market for their existence, they cannot rectify market imperfections. Rather, it is the role of the government in these cases to assure that the market operates fairly and efficiently, with as few distortions as possible.

(See Appendix B)

Recycling is one of a number of social concerns relating to the automobile. Actions to increase vehicle recyclability have significant implications for meeting other social objectives such as safety and fuel economy. A framework to help reconcile these conflicts is needed not only to help guide automaker design choice but also to frame public policy initiatives.

In the face of increasingly stringent performance requirements, automakers have worked to develop more fuel efficient vehicles while maintaining or improving vehicle performance and cost. Vehicle curb weight reduction has been the primary strategy of the automakers, leading to smaller cars using increasingly sophisticated materials. However, profitable recycling of such materials is considerably more difficult than that of the traditional ferrous materials, putting the automobile designer in a quandary: which goal should be satisfied? While the designer is equipped to balance the classical economic and engineering objectives of the firm, no tool exists which helps the firm, at any level of the organization, to articulate and resolve conflicts in the emerging social agenda.

This difficulty is compounded by the fact that these conflicts can only be resolved in a political arena. The fact that regional political forces have strong design implications for the producers of products in a global marketplace implies that both automakers and policymakers must devise mechanisms both to articulate the design implications of policy initiatives and to reconcile conflicting social and economic objectives in a politically acceptable fashion. Without such mechanisms, the ability of both the automaker and the policymaker to act effectively will be severely restricted.

(See Appendices C & D)

Improved global recycling performance for the automobile can be accelerated through concerted actions by the world automobile industry.

The industry can improve the effectiveness of materials use and the reduction of environmental impacts of poor disposal practices for end-of-life vehicles. Similarly, the industry must recognize that many aspects of recycling are local, national, or regional in nature and that global solutions to all dimensions of this problem do not exist.

While regional economic conditions militate against global action in the recycling enterprise, there are indications that the industry can act cooperatively to improve recyclability. Several recycling consortia have formed to perform research into new reprocessing technologies and to facilitate the implementation of standards in labeling and disassembly. Also, research and development of new materials technologies are being undertaken jointly with suppliers. Furthermore, there are cooperative ventures underway to develop useful life cycle analysis tools that can facilitate product design choices. The fact of these programs indicates that the industry can work cooperatively in these areas, although better coordination may ultimately lead to less duplication of effort.

Policy Theme — Recycling and the Automobile Industry

The critical point about automobile recycling policy is that the problem it addresses is ***not*** purely a problem of the automobile industry. Rather, effective recycling policies rely upon the successful confluence of action by government, automakers and suppliers, automobile consumers, automobile recyclers (dismantlers and shredders), secondary materials processors, and raw material suppliers. In fact, these requirements are shared by all consumer durables, particularly since their recycling ultimately feeds the same secondary materials markets. Actions by the automobile industry alone cannot guarantee that recyclability can be successfully increased or improved. Granted, there are some actions that can be undertaken independently, but effective improvement in recycling requires a larger strategic consideration of the technological constraints upon recyclability, the impact of actions to improve recyclability upon other automobile impacts upon the environment, upon the performance of the automobile, and upon the consumer’s willingness to pay for these changes. Furthermore, given the fact that the automobile industry is a consumer of significant fractions of the total market for many materials, the effects of dramatic action by the automobile industry will also ripple through the materials supplier industry.

Expecting the automobile industry alone to reconcile the relative importance of each of these consequences within the context of an increasingly constrained design and manufacturing situation is likely to lead to inefficiencies in both the automobile market and in the economy in general. Such inefficiencies may prove disastrous in the increasingly competitive world automobile marketplace.

At the same time, both industry and government must work together to develop policies based upon a rational consideration of options developed from a broad knowledge base. The complexity and relative fragility of the recycling industry requires that a broad perspective be taken, recognizing the factors motivating and constraining this industry. The development of successful policies in this area requires that a systematic consideration of the interrelationships between the participants is undertaken.

Recommendations

Roles For Industry

The primary responsibility of the automotive industry in the area of vehicle recycling is to assure the highest degree and most economical levels of vehicle recyclability.

Principles For Action:

- Coordinate with primary suppliers, secondary processors, and other potential users of recycled automotive materials and components to maximize the overall materials utilization efficiency.
- Facilitate the transfer of information necessary to support potential extractors and users of recycled parts and materials.
- Act to support to the secondary materials infrastructure. The automobile industry has both the financial and technical resources to assist the secondary materials operators towards more effective and economic means of separation, parts recovery, and materials recycling technologies.

Actions:

- Develop and implement international industry standards on materials marking and on limiting the number of plastics types.
- Develop improved fasteners and other joining technologies which reduce the cost of disassembly.
- Develop design support systems, indicating the life-cycle implications of design choices.
- Remove industry-imposed barriers to the use of appropriately reconditioned and re-manufactured components in automobiles.
- Choose materials, consistent with meeting other social objectives, such as safety, fuel economy, etc., that maximize recycling. Make use of secondary materials whenever their use does not limit the performance of the vehicle nor significantly impact its economics.

- Support research and development of secondary materials and materials processing technologies. Explore technical and economic mechanisms that support all pathways for materials reuse and recycling-metals, polymers, elastomers, electronic components, and parts in general.

Roles For Government

The best approach for the government in the area of vehicle recycling is to assure a smoothly functioning secondary materials economy.

Principles for Action:

Because recycling is a market-driven enterprise, government action should be to support and refine the operation of the market, rather than to direct the avenue the markets must follow. For this reason, the government must be extremely cautious when considering the following actions:

- Closed loop recycling mandates
- Fixed recycling targets
- Management and intervention in secondary materials markets

Such command and control approaches to recycling policy run very substantial risks of making the recycling system less effective and less robust.

Government action also must consider that the automobile is only one of many durable products which ultimately enter the recycling stream. Care should be taken to assure that actions to promote recycling are coordinated across all durable products.

Actions:

- Monitor the operation of the recycling industry to identify barriers to effective operation and to assure that environmental and social goals are being served by the market.
- Remove market distorting subsidies and other instruments favoring virgin materials.
- Guarantee free access to the supply of used automobiles to all credible players.
- Assure the entry of used vehicles into the secondary market.
- Provide maximum flexibility to private sector players in designing a smoothly functioning recycling system. Avoid prescribing or proscribing specific technical arrangements.
- Assure the economic viability of overall automobile recycling system to the extent that the market for recovered materials in not competitive with virgin stock or other choices. The attached analysis (Appendix C) shows that it is the overall economics as well as the performance of individual tiers in the recycling system that determine the effectiveness of materials use over the long-run.

Reaching Consensus On Future Policies And Practices

Achieving global agreements on appropriate practices and policies rests on resolving differences in values and cultural preferences. Successful recycling systems transcend purely technical considerations. The present process in severely limited by lack of adequate information of the implications of future and present activities.

Actions:

- Use this report to form a consensus on international principles on recycling that can be used to guide the development of specific initiatives and regional actions. A meeting should be convened between the industry, government, and interested stakeholders to revise and agree upon the principles presented here.
- Form an international recycling forum, composed of automobile assemblers and their major suppliers. This forum should serve as a venue for participants to discuss emerging issues in vehicle recycling and to devise strategies to meet them.
- Build on the approach taken in this recycling project to establish a model for ongoing industry efforts to develop industry policy and initiatives to meet realistic social objectives.
- Develop, with both industry and government support, new analytic frameworks that systematically consider the impacts of potential industry choices and public policy on the overall economic and environmental impact of the automobile throughout its production, use and disposal.
- Develop an information program to combat the public’s poor appreciation of automobile recycling in particular and of the emerging tension between policies directed at the automobile in general. Two opportunities in this regard are:
    - Use this document to develop a consensus among the industry, government and environmental stakeholders. Revise this document in accordance with this agreement and use it to make the public aware of the ongoing policy developments and industry actions in the area of automobile recycling.
    - Target specific “high profile” recycling problems. Inform the public about the nature of these issues and explain the actions available for their resolution, presenting the technical, economic, and environmental implications of these actions

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Automobile Recycling Policy: Background Materials

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Background Materials

The Recycling of Automobiles:
Conflicting Environmental Objectives
In A Competitive Marketplace

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Abstract

The issue of automobile recyclability is a problem with complex ramifications for car makers world-wide. Confronted with increasingly stringent fuel economy, emissions, and safety standards, recyclability is an attribute which can limit the ability of the automaker to meet these other goals economically. Nevertheless, social and political pressures upon the industry require that it responds to the perceived need for more recyclable vehicles.

These actions are already underway. However, there are crucial strategic questions which must be resolved in the face of the economic and technological limitations which circumscribe these efforts. This paper summarizes these efforts and addresses strategic issues which must be resolved.

Introduction and Background

The issue of automobile recycling is both a precursor of and a latecomer to the question of automobile environmental impact. First addressed during the late 1960s and early 1970s, vehicle recyclability has again become an increasingly visible, and therefore strategic, problem for the world automobile industry.

In their first incarnation, automobile recycling problems were a consequence of two factors:

1. Changes in the technology of steelmaking. The transition from open hearth to basic oxygen steelmaking reduced the demand for steel scrap, especially low quality (high impurity) scrap.
2. Rising labor costs. The only methods available for producing high quality steel scrap from automobile hulks were hand disassembly and separation of metallic contaminants, so increases in labor costs increased the cost of producing high quality scrap from hulks.

This combination of decreased demand in the face of rising costs was deadly for the automobile disposal industry. Without a market willing to buy low quality steel scrap, and no cost effective way to improve the quality of that scrap, old vehicles accumulated in junkyards or were abandoned, imposing both a financial and an esthetic burden on many communities [1].

Resolution of the problem took place as the consequence of two technological developments, accelerated by a special market situation. The technological developments were:

This document is based on materials presented at the KIET International Seminar on Korea’s Auto Industry, which was held November 25-26, 1993 in Seoul, Korea.

1. The rise of electric arc steelmaking, a process dependent upon a substantial source of steel scrap, and
2. The development of large scale mechanical shredding machines and magnetic separation facilities.

The penetration of these two technological developments was accelerated by an unprecedented increase in demand for all raw materials during 1972, further increasing demand for steel scrap. With a concomitant increase in demand and a decrease in the costs of production, the market for automotive scrap rapidly expanded and the “problem” of automobile recyclability receded during the 1970’s [1,2].

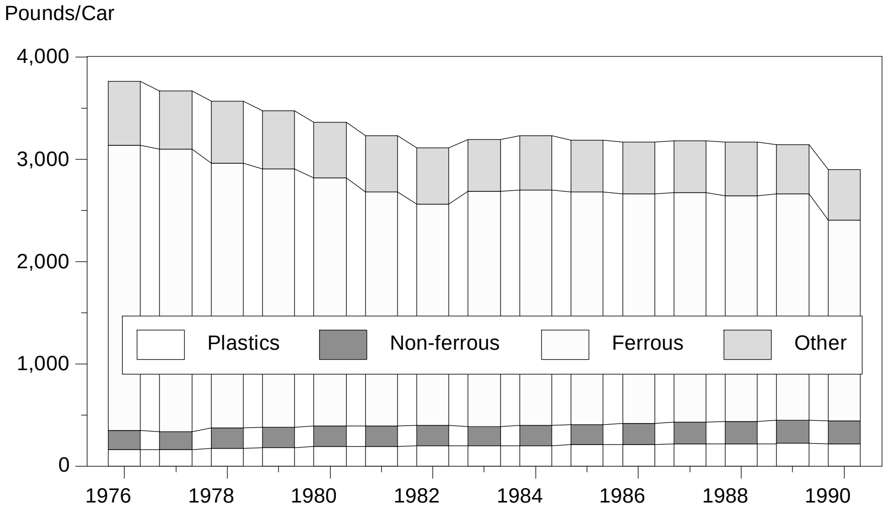
In economies with relatively free markets in steel scrap, these events led to the development of new, profitable industries which were able to extract, refine, and market old parts and the various metallic fractions of the retired automobile. In economies with limits on their markets for steel scrap or extraordinary collection problems, deposit systems were imposed to create economic incentives for the introduction of old vehicles into the disposal network [3].

During the 1970s and 1980s, the focus of automotive development was on improving the fuel economy and reducing the gaseous emissions of the automobile. Several strategies were pursued toward this end, including modifications in engine and exhaust system technologies, changes in vehicle geometry, and modifications to vehicle powertrains. However, the approach which yielded the greatest benefit on all fronts was the reduction in the curb weight of the vehicle. By reducing the vehicle weight, gains in both fuel economy and emissions per mile could be achieved.

In the early years, the weight of the vehicle was decreased through reductions in the overall size of the vehicle, the so-called “downsizing” of the automobile. However, given that there are both physical and safety limits to the degree to which downsizing is feasible, automakers also pursued the application of lower density materials. Although such materials are usually more expensive than

<u>Average Material Content of US Automobiles</u>

(pounds/vehicle - *Ward’s Automotive Yearbook*)



steel, good design and processing improvements made it feasible to achieve weight reductions through the introduction of light weight materials.

The consequences of these strategies have been striking. The automobile has become a far more fuel efficient and less polluting vehicle over the past fifteen years, despite the fact that it has also become a safer, more comfortable and relatively less expensive product over the same period of time. While there have been many controversies about how much further the automaker should go and how quickly they should get there, the efforts to date have been hugely successful and, with innovations in materials and processing, the strategy of vehicle weight reduction seemed to have a long run ahead of it.

This view has changed over the past five years in the face of a resurgence in the question of automobile recyclability. Driven by both legislative and economic forces, the past strategy of vehicle weight reduction through the application of light weight materials is facing new challenges today. Although these light weight materials reduce the energy consumed and the emissions released by the automobile during its use, they also largely compose a material stream in the existing vehicle recycling infrastructure which cannot be used, and end up as landfill. With increasing restrictions on landfill usage, this unrecycled fraction imposes an economic burden as well as an environmental burden that has the potential to reduce or eliminate the profitability of the existing automobile disposal industry [4]. In some parts of the world, this has already taken place.

While there is no consensus on the matter, the environmentalist's notion of extended producer responsibility is placing the responsibility for the disposal of the automobile at the automaker's doorstep. The 1986 German Waste Management Act establishes this as an underlying principle[5], and the view is receiving wide consideration. The problem for the industry has become a question of what can be done, and how best to implement it.

The Problem of Recyclability

At the root of the question is the issue of recyclability. Although widely discussed, there is considerable confusion about its meaning. Recyclability is both a technological and an economic issue. On the technological side, recyclability requires the existence of methods that can be used to extract the constituent materials from an obsolete product. On the economic side, recyclability depends upon the existence of a market for these extracts. Furthermore, there must be a balance between the cost of employing the extraction technology and the quality of the extract such that the recycler has an economic incentive to undertake the recycling.

This view of recyclability is reflected in both the development and the resolution of the problem of vehicle disposal in the 1970s. The critical element of this first automobile recyclability crisis was the decline in demand for secondary automotive materials. Primary steel manufacturers were uninterested in the low quality products of the automobile junkyard, whose impurities (or "tramp elements") could ruin their product. Because the cost of separating these constituents would have raised their costs well above the prices they could get for the product, junkyards simply refused to recycle anything but the most valuable parts of the car, leaving the rest to accumulate.

With the growth of electric arc furnace steelmaking, the demand for low quality steel scrap increased. Because these so-called "mini-mills" were not in the business of making high quality steel products, they could afford to use contaminated feedstocks. But, they found that “fragmented” or shredded scrap could be cost effectively cleaned up through the use of inspection and, later, magnetic separation techniques. These high speed mechanical shredding and separation facilities were highly profitable, and they helped to fuel the explosive growth of the minimill during the 1970s and 1980s [6].

The problem of automobile recycling today is also a reflection of the nature of recyclability. With the downsizing of the automobile, the metallic fraction of the automobile has reduced overall, and the ferrous fraction within that has also reduced. While there is a ready market for the non-ferrous metallic fraction, there is no demand for the other elements (largely polymers, fabrics, and glass) in the form that they emerge from the shredder. Instead, they are disposed of, usually in landfills. If landfill costs are low, the costs of the disposal of this “automobile shredder residue” (ASR) is a small fraction of the cost of operating a shredder. However, if the costs of landfill are high, the shredder may not be able to cover his costs, since there are other competing sources of ferrous scrap.

Although many observers have pointed to the rising polymeric content of the automobile as the primary culprit in the decreasing recyclability of the automobile [4,7], the problem is far more complex than the automakers’ decision to employ any particular class of materials. The automobile recycling infrastructure today is composed of several competing economic agents in addition to the automaker, each with his own set of technological and economic constraints.

The first of these agents is final operator of the automobile. In order for the junked automobile to be recycled, ownership of this vehicle must be transferred from the final owner to the first processor of the recycling stream, the dismantler. The ease or difficulty with which this transfer takes place will be a direct function of the condition of the automobile, the constituents of the automobile, the dismantler’s perceived value of the automobile, and the final owner’s desire to get rid of the vehicle. Provided that the dismantler’s perceived value exceeds the final owner’s desire to dispose of the car, the old vehicle enters the recycling stream.

The dismantler’s economic equation revolves around five factors: (1) the cost of acquiring the old vehicle; (2) the cost of extracting, storing, and distributing the parts that can be sold; (3) the price that the used parts can be sold for; (4) the cost of extracting and removing the materials that the shredder does not want in the stripped car (e.g., lead batteries, unexploded air bags, gas tanks); and (5) the price at which the stripped car (or hulk) can be sold to the shredder.

The economics of shredding depend upon five factors: (1) the cost of acquiring the hulk; (2) the cost of operating the shredder and ferrous separator; (3) the cost of disposing of the ASR; (4) the price the shredder gets for the shredded steel; and (5) the price the shredder gets for the mixed non-ferrous metal blend (largely aluminum, zinc, and red metals).

The non-ferrous separator’s profitability relies upon the same elements as do the shredder’s, except that the nonferrous separator has several different product streams that can be sold. And the economics of the disposal industry depends upon the costs of operation and the revenues garnered from their customers.

This complex web of market and technological interaction is currently in place to recycle and dispose of the de-registered or end-of-life vehicle (ELV). Roughly 75% of the automobile by weight is recovered and returned to the used parts market or the secondary metals market today. Increasing the recycled fraction of the automobile will not only require the development and introduction of new materials extraction and processing techniques, but also the recognition that the existing infrastructure is an economic system of considerable complexity and flexibility. While the automaker's choice of materials impacts this system on several levels, materials selection alone cannot accommodate all the needs of the recycling infrastructure and the needs of the automobile manufacturer. Resolution of this tension will require a system-wide perspective on the problem of vehicle production and use, material recovery, and waste disposal.

Efforts of the Industry

In recognition of this view, the automobile industry worldwide has been addressing the problem of vehicle recyclability on a variety of levels. This effort has been most extensive in Europe, where a combination of structural impediments to recycling profitability, high landfill costs, resistance to incineration technologies, and legislative mandates have compelled the industry to act. However, because the European market is becoming increasingly important to the worldwide automobile industry, the pressures upon the European industry are being responded to throughout the world.

It is instructive to examine the various approaches to vehicle recycling that are being taken world-wide. Although the following descriptions are unquestionably incomplete with unavoidable generalizations, they are a useful context within which the larger question of the automobile and its environmental impacts can be considered.

European Approaches

In a general sense, the consideration of automobile recyclability in Europe is being driven by several factors [8]:

1. High landfill costs. Between population pressures, transportation costs, and political pressures, the cost of landfill in Germany is on the order of \$100 to \$300 per ton, and much higher with toxic materials. While this situation is not universal throughout Europe (e.g., the cost of landfill in the U.K. is only roughly \$15/ton), the availability of landfill is expected to decline owing to political pressures. The resistance to transport of wastes within the E.C. is expected to exacerbate this situation.

2. Low prices for automobile steel scrap. While automobile shredder scrap is adequate for the manufacture of construction shapes, such steelmaking in concentrated in southern Europe. High shipping costs reduce the demand for automobile scrap from much of Europe. Furthermore, some countries limit the degree to which scrap can be exported, to protect their indigenous steel industry.

3. Restrictions on used parts markets. In some cases, the market for used parts is dominated by the original equipment manufacturers, while in other cases, the market is not well organized. In either case, the value of used parts to the dismantler can suffer.

These elements have combined to limit the profitability of vehicle recycling industries, raising concern about the disposal of automobiles. In some cases, such as Norway and Sweden, there have been deposit systems in place since the mid

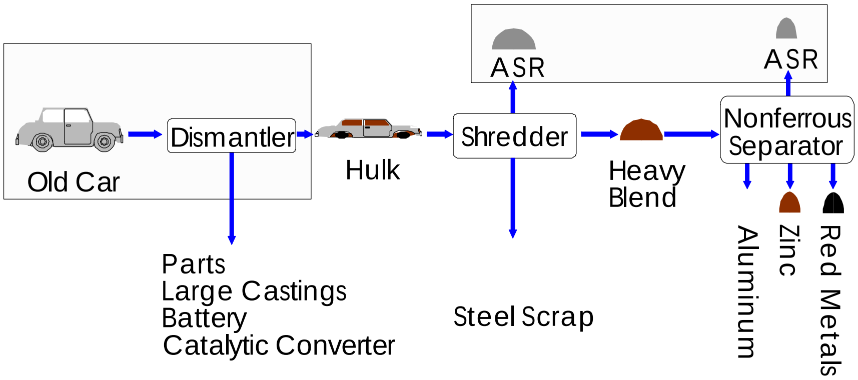
1970s to assure that end-of-life vehicles (ELVs) are in fact passed along to the dismantler, rather than abandoned. In the U.K., abandonment of vehicles is a serious problem, with only one in eight ELVs entering the recycle stream.

While the German Waste Management legislation has served to catalyze action, activity on recycling varies throughout Europe. However, because of the size of the German automobile market and the size of its industry, the German recycling proposals have received the greatest attention and contain elements found throughout the continent. In the interests of space, the German program will be described in detail, followed by a discussion of differences in other European countries.

In Germany, the government and the industry are in the midst of negotiations over a nationwide plan to reorganize and rationalize the existing recycling infrastructure [8]. Reflecting the fact that the problem requires consideration of the entire recycling system, the program has a multitude of elements. Vehicle owners will be required to collect a certificate of disposal from the dismantler in order to terminate their obligations to pay annual registration and insurance fees on their vehicles. The dismantlers will be certified (either by the industry or the government) to dismantle reusable parts, segregate valuable materials, and collect toxic compounds. Automakers will supply these dismantlers with disassembly manuals, detailing dismantling procedures and material composition for major components. The automaker will also be responsible for requiring their suppliers to take back many of these disassembled components for parts or material recovery and disposal. The vehicle hulk will be shredded, with the metallic fractions passing to the appropriate secondary markets and the shredder residue disposed of, either by landfilling or incineration.

Schematic of German Recycling Plans

(gray areas are regimes of current policy focus)



The German automobile industry will work to support this system by redesigning their vehicles to promote recyclability, in terms of increasing the ease of disassembly, striving for material compatibility, and documenting the constituents of components through labeling and disassembly manuals. Further, the industry is working to develop reprocessing technologies for the more difficult automobile materials, in conjunction with material and subassembly suppliers. Finally, the industry is developing the distribution networks that will be necessary to collect the ELVs and supply them to the dismantlers.

While this program has largely been developed by the German government and the industry working together, there are some sticking points. One is the economics of the transfer of the vehicle to the dismantler. Elements of the German government want this transfer to take place without imposing any economic burden on the owner of the ELV. The automobile industry suggests that there should be some incentive for the vehicle owner to maintain the vehicle in accordance with good recycling practice and that the market should be allowed to establish the price of the transfer. Aside from the distributional questions this issue raises (in that old cars are usually the property of less affluent households), there is also the fact that there is an opportunity cost of not recycling the vehicle, equal to another year's registration and insurance fees.

Another issue is the disposal of unusable wastes. The automobile industry is promoting thermal recovery, either through incineration for low grade heat or through a specialized metallic extraction process, where the combustible vehicle components help to fuel the process. While the popularity of incineration is low in Germany, recent events in the area of packaging recycling suggest that the government may be lessening its resistance to this approach [9,10].

While the German industry and government are still working out their plans, the French and Italians have already established recycling targets and disposal infrastructures that they expect will serve to meet some ambitious goals, in spite of their lower landfill costs. In both cases, strong liaisons with material industries and independent dismantlers form the basis for these programs, with government serving to establish targets and facilitate cooperation.

The Swedish industry is building upon its experience with deposit fees, in conjunction with certificates of deposit, to promote recycling by the last user of the vehicle. Under the current program, the deposit fee finances a system of cash reimbursement for every recycled vehicle, with the size of the reimbursement established by the condition of the ELV. Furthermore, Volvo has begun to implement a set of design tools that may prove to facilitate the selection of materials which minimize the environmental impact of the vehicle.

The Swiss and the Dutch have essentially outlawed the disposal of automobile materials in landfills within the decade, and are pursuing the development and financing of a series of incinerators. In the United Kingdom, landfill costs are quite low (below US figures) and a sizable shredder capacity is in place. However, poor vehicle recovery rates have led government and industry to pursue vehicle recycling efforts directed at improving vehicle recyclability through better vehicle design and improvements of the existing infrastructure to raise its profitability.

U.S. Approaches

In the United States, the problem of vehicle recyclability is largely driven by perceptions of the potential impacts of the European efforts. In the US, the existing vehicle recycling infrastructure is largely effective, breaking ELVs into component parts for reconditioning and resale or recovery, shredding hulks to feed a strong market for shredded steel scrap and secondary non-ferrous metals, and enjoying low landfill costs (averaging $35/ton). By and large, these activities are profitable, leading to the recovery of approximately 75% of the automobile by weight. In recognition of the trends in Europe and of the potential for similar activities at home, US automakers have entered into a number of research arrangements to develop technologies which might improve the recyclability of the remaining 25% of the automobile, as well as exploring new classes of materials for vehicle application.

A variety of structural and legal restrictions have limited the automakers to this largely developmental role. First, legal requirements to achieve fuel economy, emissions, alternative-fueled vehicles, and passenger safety take priority over a less concrete set of recycling objectives. Second, the notion of extended producer responsibility introduces potential legal and financial liabilities under existing US common law and environmental legislation, with which the automakers are loath to deal. Third, many of the programs in Europe rely upon national vehicle registration rolls tied to annual registration fees and insurance payments. In the US, vehicle registration is handled at the state and local level and removing a vehicle from the registry is relatively simple and cost-free. Fourth, the existing infrastructure operates completely independently of the automakers, and guards its prerogatives fiercely.

Thus, while the US industry has interests in vehicle recycling, their role has largely been a precompetitive and a process technology research directed one. In many respects, their recycling efforts have been taken up by their material and component suppliers, looking to develop new applications.

Japanese Approaches

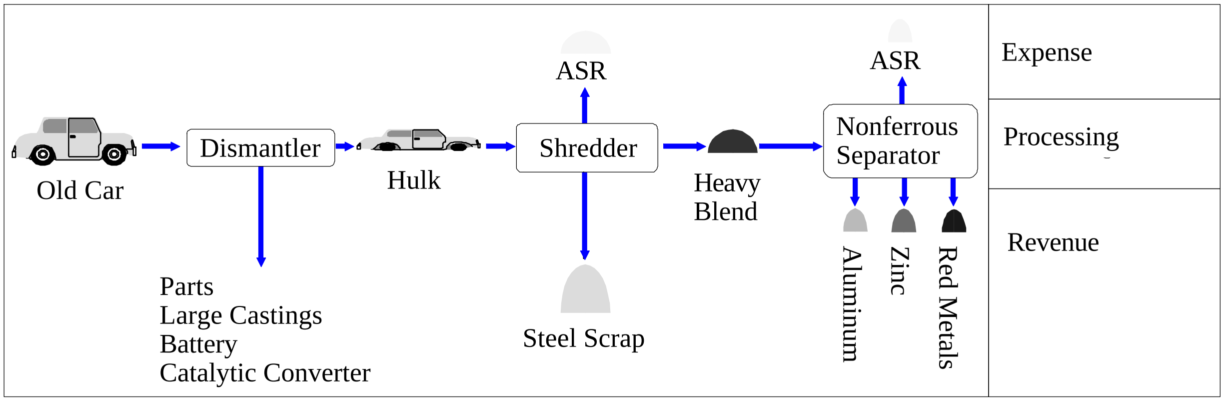
Like many of the European countries, Japan's recycling programs are driven by a decline in the availability of landfill space. Like their counterparts in the rest of the world, the Japanese recycling infrastructure recovers roughly 75% of the car by weight, landfillling the remaining blend of plastics, fabrics, and other unusable materials. Like the Germans, a set of legislative mandates has been developed to promote the use of recyclable resources, with specific provisions targeting automobiles.

In response, the industry has adopted material labeling standards, and is pursuing energy recovery from ASR as a way to reduce landfill use while reducing oil consumption. In addition, vehicle development programs are working to incorporate material and component design strategies which facilitate recyclability by reducing the costs and difficulty of disassembly and sortation. Furthermore, the Japanese automakers are pursuing a variety of material recovery and reuse programs, increasing the recycled material content of their vehicles.

Institutionally, the Japanese not only have a national vehicle registration system, but they also have an established set of procedures for vehicle disposal in place. Japanese vehicles can be disposed of only after an authorizing certificate of disposal is collected from the appropriate authorities.

An Illustrative Scenario

In order to illustrate the scope and complexity of the vehicle recycling process, a scenario based upon US recycling operations will be presented, and the impact of changes upon that basic scenario will be briefly discussed. The scenario, while reflecting US conditions, will be generally applicable to the problem of recycling of the automobile anywhere in the world, and will serve to illustrate several crucial points about recyclability [for more details, see 11, 12].

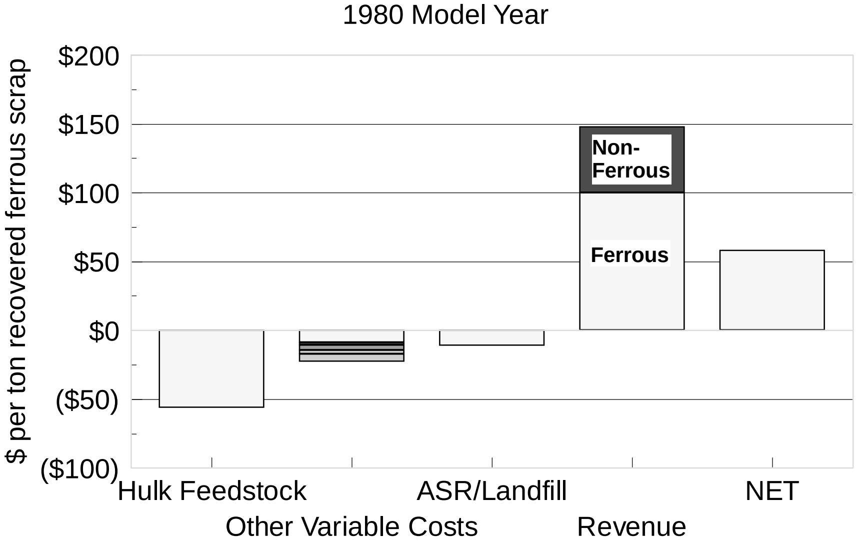


The above figure depicts the elements of the current automobile recycling infrastructure, summarizing the processes, material flows, and economic elements. In the United States, the dismantler pays $50 per vehicle on average, depending upon the age, condition, and popularity of the vehicle. Between two and four man-hours are expended to extract valuable parts, which can generate revenues of roughly $150, on average. The remaining vehicle hulk is flattened, sold (again for roughly $50), and transported to a vehicle shredding and ferrous separation facility.

Shredding is a well-established technology for fragmenting solid waste in general. A state of the art integrated shredding and ferrous separation facility costs about $5 million and can produce up to 70 tons of shredded steel scrap per hour. A crew of 10-12 is required to operate such machines, and there are high maintenance costs.

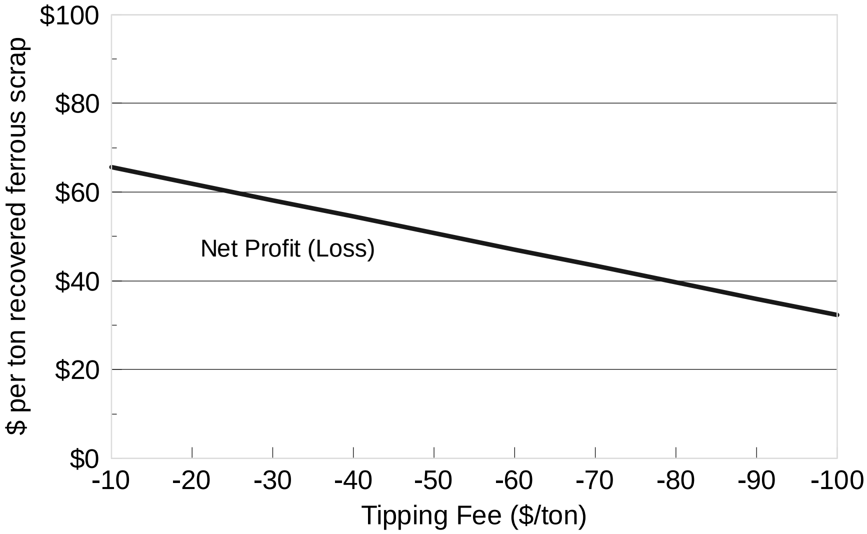
The economics of shredding can be estimated based upon current operating conditions and process technology. These assumptions are listed in the following table. Based on these assumptions and using average material content

Shredder Operation Assumption	*Value*
Capital Investment	$5,000,000/facility
Hulk Purchase Price	$50/hulk
Ferrous Scrap Price	$100/ton
Nonferrous Scrap Price	$900/ton
Landfill Tipping Fee	$30/ton
Hulk Consumption Rate	99.7 tons/hour
Ferrous Scrap Output Rate	70 tons/hour
Nonferrous Scrap Output Rate	3.7 tons/hour
Combustible Fluff Output Rate	10.2 tons/hour
Noncombust. Fluff Output Rate	15.7 tons/hour



values for a 1980 US vehicle model as the baseline, the shredder's profit for extracting one ton of ferrous scrap is roughly $55.00. Although about 0.37 tons of ASR is produced for each ton of ferrous scrap, the landfill cost is a relatively small fraction of the total operating cost under the assumed basis conditions The other variable costs (*i.e.*, transportation, energy, materials, labor, and capital) are about twice as much as the landfill cost. The metallic fraction, accounting for approximately 78% by weight of the hulk, has sufficiently high market values to compensate for ASR's relatively small cost liability. In fact, the major cost contributor is the purchase of hulks. Under the base case assumption of $50/hulk, the feedstock cost for each ton of recovered ferrous scrap is approximately $56 or 62% of the total cost. Clearly, rising hulk prices are the central factor in shredder profitability.

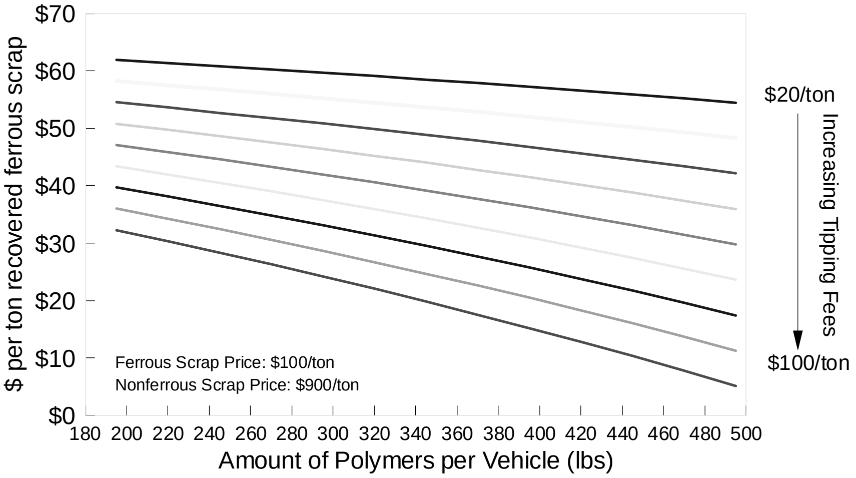
Sensitivity to Landfill Tipping Fee



When discussing recycling, one issue that invariably is raised is the increasing cost of landfilling. The base case $30/ton fee reflects the typical cost encountered in the less populated central region of the United States. This number may be on the low side given that fees have averaged a 17% increase in the 1988-1990 two year period. There are also large regional variations in tipping fees with some Northeast facilities at over $65/ton. However, as the preceding figure might suggest, the impact of landfill cost increases upon shredder profitability is relatively minor. In the preceding figure, the profitability of generating a ton of shredded steel scrap is presented as a function of landfill costs, all other factors held constant.

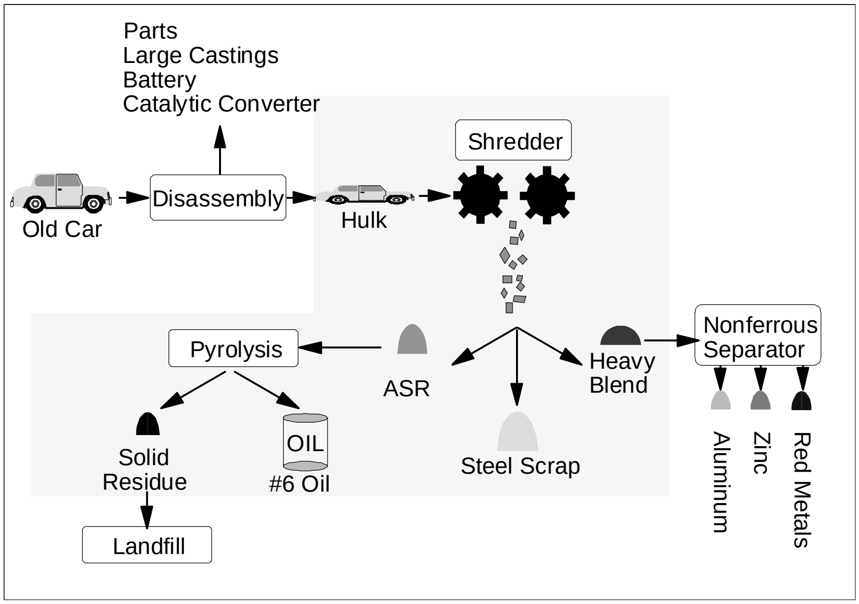
A hulk shredding operation can still achieve profitability at tipping fees as high as $100/ton. In fact, for this set of assumptions, the crossover point into net loss will not occur until approximately $190/ton.

Impact of Increasing Polymer Content and Tipping Fees



Turning from landfill costs, the automobile's changing materials content has also been implicated in the vehicle recycling problem, particularly as a challenge to shredder economics. Notably, in the absence of changes in disassembly or reprocessing technology, the increased use of polymers may lead to higher ASR landfill burden. At the same time, the decreased use of ferrous materials implies less of the marketable metallic fractions. Assuming that the plastic content of the baseline 1980 average of 195 lbs/vehicle increases to 495 lbs, and that 1 pound of plastics replaces 1.15 pounds of carbon steel (an admittedly pessimistic scenario), the shredder economics can be reconsidered for a variety of landfill tipping fees. As the preceding figure illustrates, a combination of high tipping fees, high polymer content, and a fixed hulk price is required to challenge the profitability of a shredding operation.

As a final illustration, it is possible to speculate about the implications of incorporating alternative recycling processes in the recycling infrastructure to divert these polymeric materials from landfills. One of the most actively considered processes in the US is pyrolysis, an anaerobic heating of organic materials, generating petrochemicals, ash, and heat. The most likely scenario incorporating pyrolysis in the existing vehicle recycling infrastructure would require the separation of candidate components by the dismantler, who would supply them to the pyrolysis process for a fee. However, the simplest approach would be to



pyrolyze the auto shredder residues (a currently speculative approach). The interesting question is the fee that would be required to support the operating of the pyrolysis facility in the first place.

Depending on the feedstock, reactor temperature, and residence time, the degree of organic decomposition and amount of extracted pyro-oil can be estimated. A potential ASR pyrolysis scenario is presented in the following table.

Assumed Parameter	*Quantity*
Capital Investment	$2,700,000/facility
Processing Rate	1 ton/hr
Pyro-oil Yield	33% of feedstock by weight ~67% of organic content
Pyro-oil Price	$0.26/gal.
Pyro-gas	Consumed in reaction
Solid By-product	Landfilled @ $30/ton
Pyrolysis Tipping Fee	$0
Feedstock Preparation Cost	$0 (pre-shredded and pre-sorted)

For the sake of simplicity, it will be assumed that the petrochemical product of the pyrolysis is #6 industrial oil. In reality, some lighter fractions will be evolved and used to sustain the reaction. Incomplete pyrolysis may also occur, leaving some organic matter as solids.

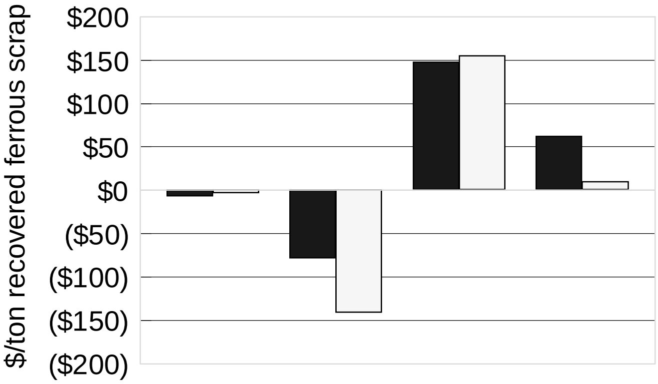
Given that the pyro-oil can be sold for $0.26/gallon and the residue landfilled for $30/ton, this particular pyrolysis facility will have a net operating loss of $165 for each ton of ASR. The cost breakdown is presented in the next figure. Recall from the hulk shredding model that 0.37 ton of ASR is produced for each ton of recovered ferrous scrap. Thus, the pyrolysis cost can be alternatively represented as $61/ton of recovered ferrous scrap.

However, tertiary and quaternary recycling processes are attractive primarily for their volume reduction potential. That is, assuming that all the incoming

ASR feedstock can be converted to and sold as oil or fillers, waste will be diverted from the landfill. If pyrolysis is treated as an alternative to landfill, then a tipping fee of $165/ton will just offset the costs of operating the pyrolyser.

Integrating the shredding economics with pyrolysis and landfilling alternatives illustrates the critical limitation to the introduction of new waste reprocessing technologies in the existing recycling infrastructure. Given the high profitability of the shredder, interest in low (or negative) profit margin processes is understandably low. While there is money being made in recycling, redistributing it throughout the infrastructure to support new, expensive processing will be very difficult to accomplish. Barring high landfill costs, existing techniques for accommodating current polymeric products and designs are difficult to support economically. And the engendering of high landfill costs merely increases the costs to society as a whole, without necessarily offering commensurate benefits.

Comparison of Two Alternative Post-Use Routes



	Landfill	All Other	Revenue	NET PROFIT
Shredder/Landfill Route ■	($7.41)	($78.71)	$148.04	$61.92
Shredder/Pyrolysis/Landfill Route □	($3.77)	($141.37)	$155.43	$10.29

The other critical inference that can be drawn from this analysis is that the likely response of the recycling infrastructure to pressures to recover a larger fraction of ELV materials will be to reduce the value placed upon hulk vehicles, the primary cost constituent of both the dismantler’s and the shredder’s costs. Given the availability of alternatives to the reprocessed materials extracted from the ELV, the only way for the dismantlers and shredders to maintain profitability will be to reduce the costs of their feedstocks, *i.e.*, old cars. This price pressure will ultimately fall on the last vehicle owner, who will find that their costs of disposal will rise.

Crucial Questions To Be Resolved

The foregoing discussion confronts the automobile industry, its suppliers and consumers, and the government with some critical issues that must be resolved in order to meet the growing importance of vehicle recyclability in particular, and overall environmental performance of the automobile in general.

What is the rationale for requiring that automobile recyclability be increased?

Although reduction in the use of landfill is the apparent motivation for the drive to increase recyclability, automobile waste is actually a fairly small constituent of most landfills. As automakers and their suppliers have become sensitized to the impact of the toxic materials which can end up in landfills, this environmental burden has actually decreased in some respects. Overall, the automobile is one of the most efficiently recycled of consumer products, particularly in light of its complexity and composition.

While polymers are the primary reason for an increase in the total landfill generated by each automobile disassembled, it is important to remember that these same plastics are responsible for increasing the fuel economy and safety of the automobile. While aluminum may offer similar advantages, the current metallurgical limitations to aluminum recycling do not promise to resolve the problem of vehicle recyclability. In fact, the existing vehicle recycling infrastructure confronts aluminum with many of the same problems that plastics face.

Recyclability of the automobile is not limited by technological feasibility; especially given that the materials employed are extracted from rocks in the first place. Rather, it is the combination of the cost of the extraction from old cars and the lower cost of equally acceptable (or better) alternatives that limits the current vehicle recycling efficiency to roughly 75%, ***wherever*** that recycling takes place.

Given the technological limitations, what sort of recycling should be the objective?

Present automobile recycling technologies do not result in so-called “closed loop” recycling, i.e., the materials extracted from the product are reused in the same component. Generally speaking, the ferrous and nonferrous automobile materials are converted into construction shapes and casting alloys. For polymers, experimentation shows that ground, recycled materials can be used in conjunction with virgin material to produce plastic components, but the applications for which these are suited are less demanding than those from which the material originally stems. Furthermore, the cost of these blends compares unfavorably with virgin material in most cases.

Closed loop recycling, in fact, is a relatively rare phenomenon. The best example (which still requires some virgin material) is the aluminum beverage can. Composed of only two alloys, with relatively minor differences in composition, and lined with plastic, the can and its alloys were designed for recyclability at the outset; otherwise the can could not have competed with the three-piece steel can. An automobile is a far more complex product, and the chemistry of its components strongly militates against closed loop recycling when disparate material species are combined.

Of course, such recycling might be more feasible if individual materials could be efficiently segregated. Labeling standards are a reflection of this.

Unfortunately, hand disassembly and separation are the only techniques which can hope to effect this segregation, and the cost of doing so would be huge.

Will the gains deriving from increased recyclability be worth the burdens that result?

Current policy instruments for effecting recycling focus upon economic incentives (increased cost of landfill, disposal deposits), specific performance requirements (recyclability targets, product take back), and creating demand for recycled materials (recycled material content, producer take back). These instruments do have the potential to increase vehicle recyclability, but at increased cost. While there are agents in the current recycling stream whose profits could be targeted to finance some of these charges, there is no effective mechanism for capturing this value (short of reorganizing and vertically integrating the entire process).

In the absence of such a mechanism, the economic burden of increasing vehicle recyclability falls upon the consumer of the automobile. While the consumer expresses interest in environmental improvement, the economics of such improvement are rarely as popular as the notion itself.

The relatively low costs of landfill versus the relatively high costs of avoiding them suggests that there are serious discrepancies between the social goals of recyclability and the willingness of society to pay to achieve these goals. In the face of public suspicion of industrial activities in general and of the automobile industry in particular, reconciling the economic and technological pressures that recyclability imposes with the political mandates that government is responding to will require a new framework for negotiation between the interested stakeholders, rather than the kind of experimentation that is being undertaken in various parts of the world today.

Is recyclability an issue of landfill use reduction or an issue of resource conservation?

An important issue that the recycling conundrum exposes is the ultimate objective of recycling. This issue is exposed whenever the question of incineration is raised in this context. On one hand, incineration looks like the perfect solution to the problem. There are effective technologies for extracting useful energy from ASR (which has a surprisingly high heat content) without producing dangerous gases. Furthermore, once the incineration is complete, the remaining ash occupies only a fraction of the space that would have been required by the ASR. However, incineration is an unpopular option, not only because of concerns about the safety of the operations, but also because it consumes resources that might otherwise be reused.

The question this raises is whether landfill use reduction is more important than resource conservation, and what is the role of recycling in furthering these goals. Presently, there are a several technologies which reduce landfill burden by employing the thermal value of the various material species in the automobile to drive material recovery processes or to produce energy. These processes are under consideration because they may prove to be less expensive than high priced landfilling. However, these processes consume materials that might otherwise be reprocessed. If landfill reduction is the critical objective, then these processes might be appropriate; if resource conservation is the goal, then these processes might represent an inefficient use of a scarce resource.

Of course, the recycling issue also exposes other questions of environmental prioritizing. Because weight reduction also has environmental implications, the extent to which recyclability suffers as these other environmental goals are furthered establishes a tension which cannot be resolved by either government or industry operating alone. Rather, these two actors, in conjunction with other stakeholders, must find a stable basis for reconciling these competing goals. Otherwise, neither the economic objectives of the firm nor the social objectives of government will be effectively pursued.

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A Systems View of Recycling

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Introduction

One way to consider the policy implications raised by initiatives to increase the recyclability of the automobile is to start with a consideration of the existing methods for resource recovery from old automobiles. Figure 1 summarizes the way in which automobiles are currently recycled in most of the world today. This diagram presents the major actors in the recycling of the automobile: the last user, the dismantler, the shredder, the non-ferrous metals processor, and the markets for used parts and scrap metals. The smaller activities within this infrastructure are not represented. These smaller operations and interactions include the processing and treatment of the lead-acid battery, the catalytic converter, the air bag, and the gas tank. Further, the dismantler may not choose to resell the large metal parts (like the engine block and the transmission housing) to the used part market, but may instead merely sell them in the scrap metal market. Nevertheless, the figure captures the major interactions in the recycling infrastructure

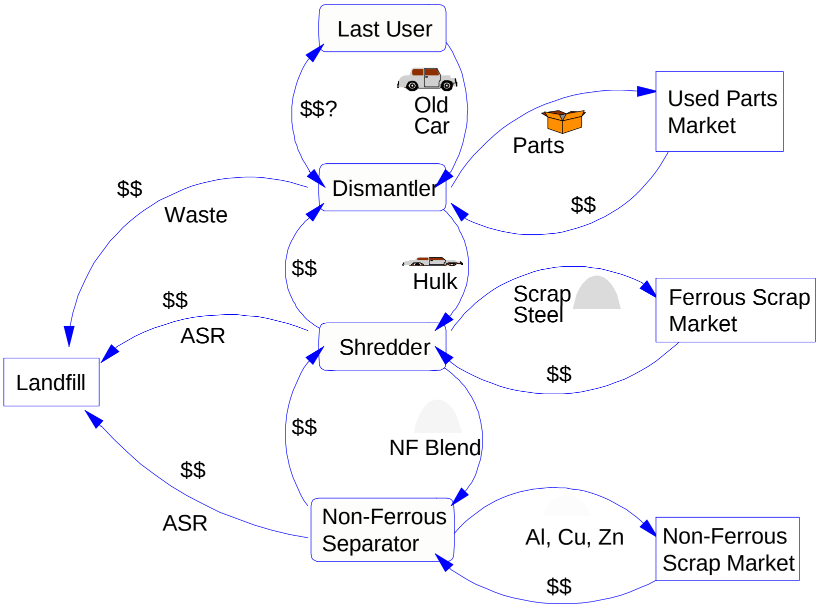


Figure 1: Existing mechanisms for resource recovery of materials from automobiles

Unlike more common representations of this infrastructure, however, Figure 1 shows not only the flow of materials through this infrastructure, but also incorporates the economic flows which accompanies these material flows. This figure makes explicit the feature of recycling that is most commonly forgotten: nothing is truly recyclable if there is no market for the recyclate. Collecting and generating recyclate is no guarantee that there is a demand for the resulting resource. Similarly, the interactions between the participants in the recycling infrastructure will only occur if the financial incentives are sufficiently large.

Reviewing Figure 1, the only financial flow whose direction is uncertain is the flow between the dismantler and the last user. Depending upon the situation, the dismantler may pay for, or be paid to take, the old vehicle. Thereafter, however, the transfer of resource must be accompanied by a reciprocal flow of financial assets, while the transfer of waste requires a parallel flow of cash.

Efforts to increase the amount of the automobile recycled depend either upon increased effort by the existing processors, or the participation of one or more new processors. Generally speaking, most of the initiatives in the area of increased automobile recycling are targeted at the introduction of processes and mechanisms that lead to increased recovery of the polymeric fraction of the automobile. These new processes are likely to rely upon the existing recycling infrastructure to supply the necessary feedstocks, either in the form of plastic parts removed by the dismantler or in the form of automobile shredder residue (ASR), the blend of chopped materials separated from the ferrous and nonferrous scrap metals. Figure 2 presents this potential expanded recycling framework. It is important to note that not only are new processes required, but also new markets for the materials extracted.

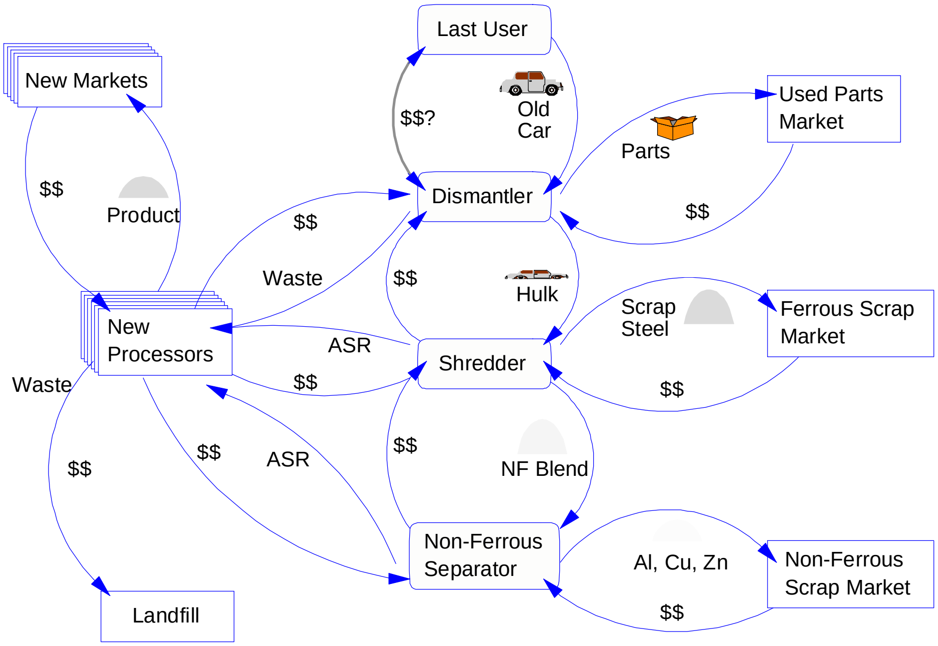


Figure 2: Mechanisms for expanded resource recovery of materials from automobiles

The maze of linkages represented in Figures 1 & 2 amply demonstrates the complexity of the infrastructure for recycling and the myriad interconnections and interrelationships between the actors. However, the important relationships between these actors are a reflection of some simple economic factors which can be presented in a fashion that begins to reveal crucial structural features of this market. In particular, the fact that recycling occurs in response to economic opportunity rather than technological necessity suggests a closer consideration of the economic transactions between the actors. By constructing a representation of the expenses and revenues of each participant, a clearer picture of the important aspects of the recycling infrastructure emerges.

The relationships between the actors in Figure 2 can be presented in a tabular form that can be used to articulate the necessary conditions for a successful recycling infrastructure. In Figure 3, the flow of income and expenses within the recycling infrastructure is presented, incorporating not only the major interactions presented in the preceding figures, but also some of the alternative material flows (e.g., the sale of large metal parts as scrap metal rather than as used parts).

In Figure 3, a ‘+’ signifies an income-generating transaction by the actor in that row, while a ‘-’ signifies a purchasing transaction by the same actor. The column in which the ‘+’ or ‘-’ appears indicates which other actor participated in the transaction. In other words, each ‘+’ and ‘-’ corresponds to a purchase or a sale by the actor in the row in which the symbol appears with the actor in whose column the symbol appears.

		Source of Income/Recipient of Expense									
	Actor	A	B	C	D	E	F	G	H	I	J
A	Last User	-V	+/-								
B	Dismantler	-/+	-P	+		?	+	+	+		-
C	Shredder		-	-P	+	?		+			-
D	Non-Ferrous Separator			-	-P	?			+		-
E	New Processors		?	?	?	-P	+?	+?	+?	+	-
F	Used Parts Market		-			-?	+V				
G	Ferrous Scrap Market		-	-		-?		+V			
H	Nonferrous Scrap Market		-		-	-?			+V		
I	New Scrap Market					-				+V	
J	Landfill		+	+	+	+					-P

Figure 3: Tabular representation of asset flows within a stylized automobile recycling infrastructure. The flows are characterized according to the Actor, so a ‘+’ signifies income while a ‘-’ signifies an expense.

When actors process resources to extract valuable products, a ‘-P,’ which signifies the costs of that processing, appears in the gray box for that actor. Thus, a ‘-P’ appears in the rows for the dismantler, the shredder, the non-ferrous metals separators, the potential new processor, and the landfill operator. For these actors, their row in the table can be thought of as an operating balance sheet. On the other hand, a ‘+V’ represents the value of the resource flowing *into* the relevant market, or a ‘-V’ *from* the last user. This value may be a true market value, or may represent the opportunity cost that the holder of the resource faces if he is unable to sell the resource. In either case, this ‘V’ term represents the upper limit on the price that the resource would garner on the open market.

Finally, if there are free markets, the off-diagonal elements of the matrix (representing the transactions between actors) must be symmetric, i.e., for every buyer there must be a seller. This symmetry has a further implication: it couples the economics of all the recycling actors and introduces the critical operating constraints on the system. In particular, the net sum of income and expenses in each row representing a recycling processor (the dismantler, the shredder, the non-ferrous separator, and the hypothetical new processor) must be positive if the activity in that row is sustainable; i.e., each actor must make an economic profit. In addition, for each row representing a market, the net cost must be offset by the market value of the resource (parts, scrap metal, or other product) or the market will not absorb the product of the processors. An additional implication is that, absent other market initiatives, the value of these resources cannot exceed the value of virgin resources. Finally, the sum of the diagonal elements must be greater than or equal to zero, or the entire recycling infrastructure represents a net economic loss.

This systemic representation of the asset flows within the recycling infrastructure is an important basis for analyzing potential policies directed toward increasing the recyclability of the automobile. For example, while increases in the cost of landfill may lead to increased recycling (since processors will try to change their operations to limit their landfill costs), this table shows that such process changes will only take place if the change in the processing cost P is offset by a reduction in the total landfill cost and by an increase in revenue from the recyclate. If the offsetting changes are not sufficient, then increases in landfill costs will not lead to increases in recycling — rather, such price increases will reduce the profitability of the existing processors, possibly fatally. Similarly, efforts to increase the flow of old cars into the system by imposing disposal certification procedures (and imposing penalties if such certificates are not received) may merely lead to a decrease in the price paid (or even a fee charged) by the dismantler to take the vehicle (since such policies essentially decrease the value V of the old car to the last user).

Implications for Recycling Policy Options

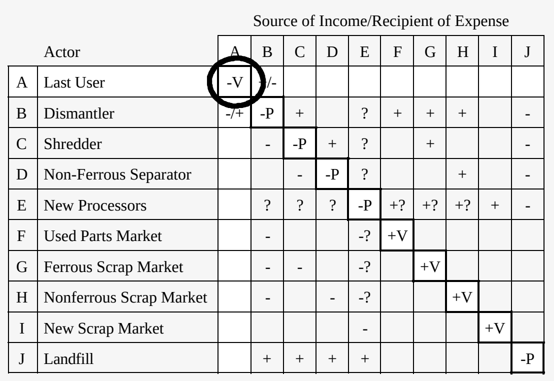
This analysis suggests that the real issues in increasing recycling, and the appropriate foci for policy action, lie along the diagonal of the table in Figure 3. While policymakers *can* intercede in the market transactions themselves, the history of such actions in materials markets has not been encouraging. Frequently such intercessions have resulted in the development of a large bureaucracy to monitor these transactions and the development of black market, with the associated market inefficiencies. This history suggests that, whenever possible, policy actions should focus on reducing the costs of the processing technologies (the **P**s in Figure 3) and increasing the market value of the resources being handled in the recycling infrastructure (the **V**s in Figure 3).

For example, while a certificate of deposit can increase the effective value of the vehicle, it does so by introducing an action during the transaction (the exchange of vehicles for certificates). Thus, while it *may* increase recycling, it may also merely allow the dismantler to capture extraordinary revenues, with no net increase in recycling. Only by introducing a way to monitor the transaction between the final owner and the dismantler can the policymaker assure that the effective increased value of the old vehicle will be transferred to the infrastructure, increasing the rate of recycling.

So, increasing the economic benefit of recycling, and thereby increasing the rate and type of recycling, must be implemented through actions that change the value of the resources being treated or reduce the costs of processing and extracting these resources. Further, these changes must be implemented in such a way that they do not rely upon monitoring and controlling the exchange transactions within the infrastructure. With these constraints in mind, the major policy options available to increase recycling can be classified according to their impact on the transactions matrix: (1) value of the old vehicle, (2) processing costs for existing or new recyclers, (3) value of recycled materials or parts, and (4) the cost of landfill.

Value of Old Vehicles

Unlike the other resources in this infrastructure, the value of the old vehicle is derived from the profitability of the rest of the infrastructure. In some sense, while there are markets for ferrous scrap and remanufactured parts independent of the vehicle recycling infrastructure, this infrastructure *is* the market for old cars. In the absence of an alternative, this infrastructure therefore is in a position to dictate this value.



		Source of Income/Recipient of Expense									
	Actor	A	B	C	D	E	F	G	H	I	J
A	Last User	-V	+/-								
B	Dismantler	-/+	-P	+		?	+	+	+		-
C	Shredder		-	-P	+	?		+			-
D	Non-Ferrous Separator			-	-P	?			+		-
E	New Processors		?	?	?	-P	+?	+?	+?	+	-
F	Used Parts Market		-			-?	+V				
G	Ferrous Scrap Market		-	-		-?		+V			
H	Nonferrous Scrap Market		-		-	-?			+V		
I	New Scrap Market					-				+V	
J	Landfill		+	+	+	+					-P

The source of value for the old vehicle is the value of the parts and the materials composing it. This value can be increased by increasing the value of these materials and parts (see below), but another strategy is to use materials in the vehicle which are readily segregated and recycled, increasing the profitability of the rest of the recycling infrastructure by reducing the costs of processing. This approach would suggest that the responsibility for establishing and maintaining this value lies with the automaker, with the supplier of after-market parts, and with the user.

The vehicle producer can increase the value of the old vehicle by designing for recycling, which has implications for materials choice, component design, and the way in which the vehicle is assembled (specifically, the ease with which assembled vehicles can be disassembled and the various materials species can be identified and separated). The component supplier can also work with the automaker to simplify disassembly and to ease the identification of the materials composing his part. Finally, the user can also maintain the value of the vehicle through maintenance and the use of replacement components manufactured in accordance with these objectives.

It is important to distinguish these actions from the various instruments that have been used and proposed for use to supposedly raise the value of the automobile and promote recycling. The deposit fee system, which has been instituted in several locales, increases the value of the old vehicle through the disbursement of cash to the last user when the vehicle is given to the dismantler. However, while this raises the value of the vehicle to the last user, none of that value accrues to the recycling infrastructure itself, which only is in a position to garner the revenues that will derive from conventionally processing the vehicle. An alternative approach, the requiring of proof of vehicle disposal before releasing the last vehicle owner from the obligation to pay property taxes, registration fees, and insurance on the vehicle, effectively lowers the value of the vehicle to the last owner, while keeping the value of the vehicle in the eyes of the dismantler intact. In this case, the dismantler is in the position to collect extraordinary income, again without any particular reason to increase the rate of material recycled from the vehicle.

Processing Costs of Existing Recyclers

Reducing the processing costs of the existing processors will require improvements in the technologies employed in segmenting the automobile and segregating the available materials and parts.

		Source of Income/Recipient of Expense									
	Actor	A	B	C	D	E	F	G	H	I	J
A	Last User	-V	+/-								
B	Dismantler	-/+	-P	+		?	+	+	+		-
C	Shredder		-	-P	+	?		+			-
D	Non-Ferrous Separator			-	-P	?			+		-
E	New Processors		?	?	?	-P	+?	+?	+?	+	-
F	Used Parts Market		-			-?	+V				
G	Ferrous Scrap Market		-	-		-?		+V			
H	Nonferrous Scrap Market		-		-	-?			+V		
I	New Scrap Market					-				+V	
J	Landfill		+	+	+	+					-P

In the case of the dismantler, this will require the transfer of information from the automaker to the dismantler in the form of material specifications and disassembly instructions. Such efforts are already underway to meet the requirements of the German recycling initiative. Similarly, both the ISO and SAE have developed labeling standards for plastic components which identify the material composition.

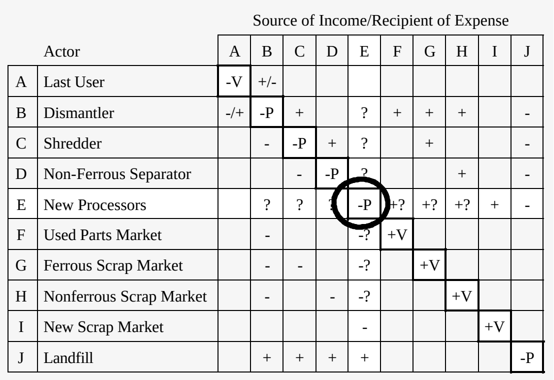
Beyond these initiatives, alternative methods for removal of components and identification of material composition could be explored. For example, it may not be necessary to remove plastic body panels intact, if the only purpose in the removal is to recover material. Similarly, while labeling can help in identifying material composition, an automated method for retrieving this information could reduce sortation errors, a critical problem for many of the experimental dismantling and polymer material recovery facilities today.

In the case of the shredder, the costs of processing are already quite low. However, as electric arc furnace steelmakers begin to explore the production of steel sheet, it will become increasingly important that the shredder achieve better control of material separation. While some tramp elements can be accommodated when making construction shapes (e.g., reinforcing bars and wires), sheet making is not as forgiving and, in order to continue to supply scrap to these producers, the shredder will have to expend more resources to produce clean scrap from automobiles.

The problem of segregation has the potential to become a much greater problem for both the shredder and the non-ferrous processor as the ferrous fraction of the automobile decreases and the use of light metals increases. Current technologies for separation rely upon gross differences in density and electromagnetic properties of the various metal species. However, with increasingly sophisticated alloys, these producers will need to find ways to make fine distinctions between these alloys. In some cases, failure to achieve this degree of separation may even lead to saturation of low quality secondary markets, which could adversely effect the economics of the entire infrastructure.

Clearly, policies directed at the development and promulgation of more effective separation technologies will be necessary to maintain and improve the economics for these existing processors.

Processing Costs of New Recyclers

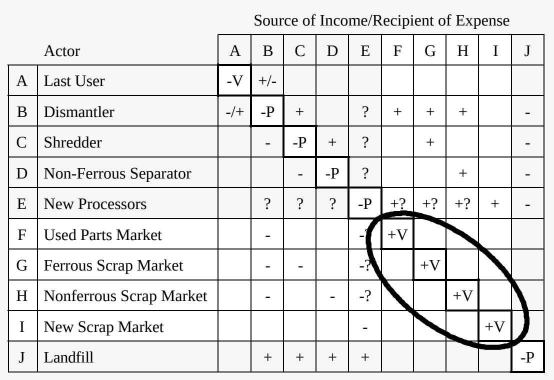


	Actor	A	B	C	D	E	F	G	H	I	J
		Source of Income/Recipient of Expense									
A	Last User	-V	+/-								
B	Dismantler	-/+	-P	+		?	+	+	+		-
C	Shredder		-	-P	+	?		+			-
D	Non-Ferrous Separator			-	-P	?			+		-
E	New Processors		?	?	?	-P	+?	+?	+?	+	-
F	Used Parts Market		-			-?	+V				
G	Ferrous Scrap Market		-	-		-?		+V			
H	Nonferrous Scrap Market		-		-	-?			+V		
I	New Scrap Market					-				+V	
J	Landfill		+	+	+	+					-P

In order to establish new processors, it will be critical that the costs of the existing processes be reduced, or new processes be developed. The economics of the available processes for the extraction and recovery of polymers are not particularly attractive, even with strenuous efforts to provide relatively clean feedstocks. When the more likely feedstocks are processed, the economics are even less attractive.

There are consortia in place to explore the development of these technologies, some of which are receiving support not only from industry but also from governments. Such policies are necessary in order to reduce the likely costs of new recyclers.

Value of Recycled Materials and Parts



	Actor	A	B	C	D	E	F	G	H	I	J
		Source of Income/Recipient of Expense									
A	Last User	-V	+/-								
B	Dismantler	-/+	-P	+		?	+	+	+		-
C	Shredder		-	-P	+	?		+			-
D	Non-Ferrous Separator			-	-P	?			+		-
E	New Processors		?	?	?	-P	+?	+?	+?	+	-
F	Used Parts Market		-			-?	+V				
G	Ferrous Scrap Market		-	-		-?		+V			
H	Nonferrous Scrap Market		-		-	-?			+V		
I	New Scrap Market					-				+V	
J	Landfill		+	+	+	+					-P

The maintenance of a healthy market for recycled materials and parts will rely upon sustaining the value of these recovered resources. This will require supporting the development of an infrastructure that can effectively remanufacture and distribute used parts, as well as support by the original equipment manufacturers for a market in secondary components. This may either require the direct participation of the OEMs in this market, or an acceptance of the loss of a certain fraction of the after-market parts market in order to support this industry.

In the case of materials markets, direct action in the secondary markets will be difficult. There are substantial difficulties with establishing and maintaining direct price supports for secondary materials, since the virgin materials market will always be able to supply a perfect substitute for recycled materials. Furthermore, establishing direct supports for recycled material prices begins to move the area of policy action off the gray diagonal, into the monitoring of transactions between buyers and sellers of recycled materials. For example, if one wishes to support the price of recyclate, one must have some way of guaranteeing that the material being sold is recyclate (rather than virgin) and is of the appropriate composition and quality.

This suggests that, rather than directly supporting the price of recycled materials, it may be appropriate to develop instruments which raise the cost of the alternatives to recyclate.

Cost/Price of Landfill

		Source of Income/Recipient of Expense									
	Actor	A	B	C	D	E	F	G	H	I	J
A	Last User	-V	+/-								
B	Dismantler	-/+	-P	+		?	+	+	+		-
C	Shredder		-	-P	+	?		+			-
D	Non-Ferrous Separator			-	-P	?			+		-
E	New Processors		?	?	?	-P	+?	+?	+?	+	-
F	Used Parts Market		-			-?	+V				
G	Ferrous Scrap Market		-	-		-?		+V			
H	Nonferrous Scrap Market		-		-	-?			+V		
I	New Scrap Market					-				+V	
J	Landfill		+	+	+	+					-P

The final area for possible policy action lies in the area of manipulating the cost of landfill. While there are some ‘real’ economic bases for the price of landfill (land prices, processing, etc.), the price of landfill increasingly is a reflection of scarcity, usually as a consequence of local and national policies. Difficulties in siting landfill, including expensive permitting and litigation processes, as well as government policies establishing varying grades of waste and associated disposal requirements, have led to a price spiral in landfill costs in many parts of the world.

On one hand, such increases in cost can lead to increases in recycling, but only to the extent that the costs of processing & extraction and the value of the recovered material leads to lower net costs than the costs of landfilling. Provided such technologies are available, then increasing landfill costs can be effective. However, there is a redistribution of income, since landfill operators (or collectors of fees from landfill operators) will accumulate economic value that would otherwise have accrued to the recyclers. Furthermore, if effective technologies are not available or the loss in economic value is sufficiently great, then the imposition of such landfill costs will only serve to choke off recycling altogether by reducing the overall profitability of the enterprise.

Life Cycle Analysis and Its Role in Product & Process Development

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Abstract

Life cycle analysis (LCA) has been described by its proponents as an environmental panacea, capable of providing engineers, designers, and managers with everything that they need to make environmentally correct decisions. Unfortunately, the goals of the technique and the reality of its application are very different. Like any analytical technique, its application requires the imposition of assumptions to accommodate limitations in budgets, resources, and know-how. Furthermore, the evaluation of the analytical results introduces questions of strategy and priority that are currently unresolved. Thus while the concepts underlying LCA are readily understandable, the practical application of the method has substantial problems.

This paper discusses the concepts of life cycle analysis and the practical limitations of the technique, based upon a review of current applications and issues in decision analysis.

Introduction

Since the early 70s, environmental regulations have continuously become more stringent, forcing companies to make environmental concerns a larger part of their product and operating decisions. This trend is particularly true in the automobile industry, which has been the target of environmental regulations with regard to tailpipe emissions, chlorofluorocarbons (CFCs), and energy consumption during vehicle use, along with air and water emissions from manufacturing. Pressures by consumers, local communities, and shareholders to reduce still further the environmental impact of automobile products and their production have intensified in recent years.

While the oil shocks of the 1970s and the US concerns for urban air quality drove the first major round of environmental legislation affecting the automobile, today’s environmental considerations are driven by concerns that are both more sophisticated and more unstructured than they were in the past. Although environmental initiatives have become increasingly elaborate, reflecting technological and scientific advances, agreement about the actual social objective and therefore the benefits of these initiatives is increasingly unclear. Without such agreement, business cannot expect to develop and implement the necessary innovations

Three current automobile developments, each motivated by environmental concerns and each increasingly suspect in light of wider considerations, illustrate the problem:

- Vehicles using fuels other than gasoline

- Electric vehicles
- Light-weight vehicles

In each case, the current engineering approaches introduce new environmental issues that policymakers apparently either did not or could not consider. Light weight materials, such as polymer composites and aluminum, while reducing the curb weight of the automobile, also can reduce the recyclability and the safety of the automobile. Alternative fueled vehicles, which reduce the amount of petroleum consumed in transportation, may lead to new types of air pollution and to a net increase in energy consumption. Electric vehicles, while possibly reducing the total amount of vehicle-derived pollutants in the air, will require the use of new classes of materials, powerplants, and vehicle structures, each with their own disadvantages.

In short, while there are technological solutions for each of these design goals, there are no clear indications that the approaches being taken actually lead to a more environmentally beneficial product. In the absence of a framework for making this determination, progress toward any of these goals will be problematic. These questions cannot be answered solely on a technological, environmental, or economic basis. Rather, it will be necessary for the automobile industry to evaluate the technological alternatives in such a fashion that all three of these criteria are addressed, over the entire “life” of the product, including manufacturing, use, and disposal.

Life cycle analysis (LCA) has become one of the most actively considered techniques for the study and analysis of strategies to meet environmental challenges. LCAs strengths derive from its roots in traditional engineering and process analysis, and from the recognition, implicit in its formulation, that the consequences of technological undertakings are not limited to the performance of a single process or change. Rather, most of the consequences of any action can derive from it, and can only be perceived when the entire range of consequences of that action are taken into consideration. The application of this technique promises to change the way that environmental considerations are treated within the larger concerns of modern technological society. However, with the rise of converts to the technique, there are indications that some of the problems that LCA is expected to solve are outside the scope of its practical and conceptual boundaries.

A wide range of potential users are interested in the application of this technique. Process and product developers are interested in LCA as a way to incorporate environmental considerations into their design process, making it possible to anticipate and avoid potential pitfalls. Consumers and consumer interest groups see LCA as a way to better inform the customer of the relative environmental impact of alternative products, hoping to bring market pressures to bear upon producers. Finally, regulators and policymakers see LCA as a tool that can guide environmental policy development and can provide a mechanism for enforcement of legislative objectives.

Overall, the primary motivation for developing LCA has been the need for a guide to action that is informed by the growing social importance of environmental objectives. With the increasing recognition of environmental issues, there has been a rising need to understand how the day-to-day activities of society can serve these considerations. The principal tool for translating consumer interests into technological action, the market, relies upon the availability of information that is well outside the capabilities of the existing infrastructure to supply. Because the complexity of the modern industrial economy makes it difficult to perceive directly the impacts of any individual action upon the environment, LCA is being developed to produce a framework within which this information can be collected, refined, and acted upon.

However, there are limits to the ability of analysis of any kind to resolve complex problems. This is particularly true when an action has consequences that advance some objectives while hindering others. Under these conditions, the choice among alternatives must not only incorporate analytical elements, but strategic ones as well. LCA is well-suited to supplying these necessary analytical elements; however, the strategic ones are well outside the scope of the technique

Life Cycle Analysis

The basic objective of LCA is to guide decisionmakers, whether consumers, industrialists, or government policymakers, in devising or selecting actions that will serve to minimize the environmental impacts while furthering other objectives. Thus, this tool must act in concert with traditional motives for selecting one action over another, including economic, engineering, and social goals.

The life cycle paradigm requires that consideration must be given not only to the immediate impacts of a product or process choice, but also to the products and processes that gave rise to that choice and to the products and processes that occur in response to that choice. This view reflects the notion that, just like the natural ecology, the ‘industrial ecology’ is a vast network of interconnected activities where the size of a change is no indicator of the scope of its effect and care must be taken to eschew local optima in favor of global optima.

Life cycle analysis is regularly presented as a three step process:

1. The identification and quantification of energy and resource use and environmental releases to air, water, and land (inventory analysis);
2. The technical qualitative and quantitative characterization and assessment of the consequences on the environment (impact analysis); and
3. The evaluation and implementation of opportunities to reduce environmental burdens (improvement analysis).[1]

The three stages of LCA reflect classical technical decision making procedures. In each case, these problems are first reduced to a control volume, across which resource flows are measured. Next, the relationship between these flows and the underlying scientific and technological principles are determined. Finally, the problem is resolved based upon the insight gained from these principles and upon the objectives of the analyst.

Much of the focus on LCA has been upon the ***How?*** and the ***What?*** of its undertaking. Organizations such as SETAC and US EPA have worked to develop a complete set of procedures for the collection and organization of the information that must be developed in the course of a LCA [1,2]. However, determining what to do with this information, once it is collected, has left many observers at a loss. Expressed simply, the objective of employing LCA is to develop activities which reduce environmental impact. Unfortunately, for all but the simplest of situations, determining how this general objective informs specific problems is extremely difficult — a fact recognized by increasing numbers of LCA practitioners.

This difficulty arises from several sources. The most apparent of these is the fact that current understanding of the relationship between releases to the environment and environmental damage is still in its earliest stages; particularly when many such releases must be considered together. However, this difficulty apparently has not limited the development and application of LCA methodology.

‘Life-cycle analyses (LCAs)’ are receiving increasing consideration by industry and government policymakers to meet these needs. However, the technique in its current incarnation is critically flawed when used as a policymaking tool.

- First, LCAs do not consider the costs of the possible alternative strategies under consideration. Instead, they tend to focus upon resource consumption, emissions, health effects, and ecological impacts. These are important considerations when choosing among alternatives, but no policy can be adequately evaluated without an understanding of its economic implications.
- Second, current LCA methodologies are based upon an exhaustive process of data collection, characterizing in minute detail every resource, material, and emission involved in the process or product being analyzed. The product of the analysis is frequently a mass of data, too large for anyone to evaluate or to base a decision.
- Third, all LCA tools under development today develop a static description of the impacts of an existing product or process - a ‘snapshot’ of environmental impact. For a decisionmaker, the critical requirement of any tool for evaluation is that it can be used to assess the consequences of change and thereby to develop a strategy for action. However, the data requirements of current LCA methods make it impossible to perform an evaluation in advance of implementation.

What has proven to be the most complicated aspect of LCA has been the final, “improvement analysis” component. Improvement analysis implicitly assumes that it is possible to discern the ‘best’ action from a set of possible actions that might be taken. Aside from simple cases where it is possible to find an action which reduces all impacts on the environment, this ‘best’ choice depends upon the relative importance placed upon each of the possible consequences that are indicated by the analysis. This relative importance is a reflection of the strategic objectives which underlie the problem under consideration, rather than any purely analytical evaluation. Because of this distinction, there are substantial hurdles that have to be overcome before LCA can be applied to broad questions of industrial and social policy.

Review of Valuation Concepts

This difficulty can be best understood by considering the general problem of valuation [see 3]. The following figure depicts a hypothetical set of potential alternatives, each of which has (for the sake of illustration) only two characteristic environmental impacts, A and B. Assuming that only one alternative can be chosen, and that the objective is to reduce environmental impact, which alternative should be implemented?

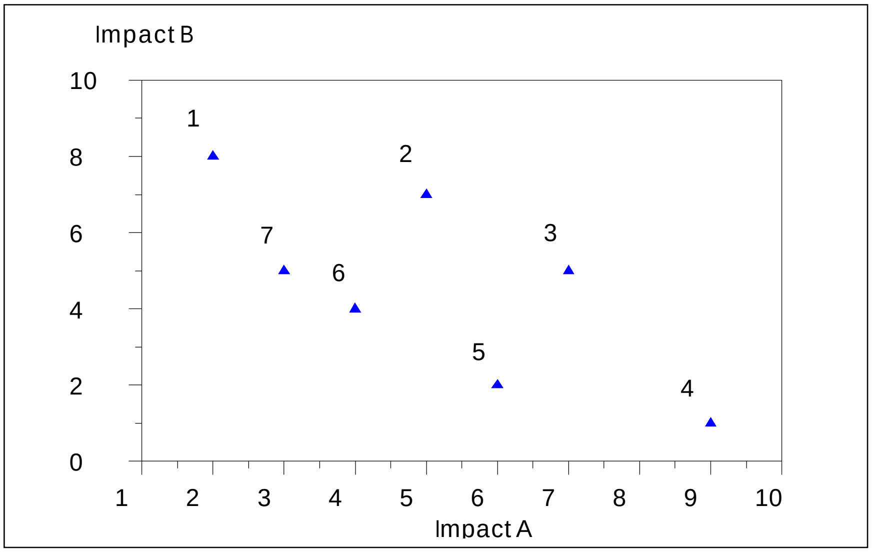

Figure 1: A set of seven alternatives with different impacts on the environment, A and B

It is easy to reject alternatives 2 and 3, because there are other choices (alternative 7, for example) that offer reduced levels of both Impact A and B. Alternatives 2 and 3 are members of what is known as the "*dominated set*" of alternatives, which are clearly inferior to others. In environmental terms, rejection of the dominated alternatives is an expression of the so-called Precautionary Principle, where any action that unequivocally reduces all environmental impact ought to be taken. Similarly, an LCA showing that a facility was operating at Point 3 would lead to the implementation of an alternative (5 or 6) reducing all impacts upon the environment.

The difficulty arises when a choice must be made among alternatives lying on the lower edge of the frontier. Which one of these is the 'best' way to operate? Decision analysis refers to these remaining points as the set of *non-dominated alternatives*, meaning that no member of the set is better than the others ***in all respects***. Rather, some are better in one or more aspect, but worse in at least one other.

Selecting from among members of the non-dominated set of alternatives is one of the central questions of decision analysis, and is frequently referred to as multiple-objective decisionmaking. The name arises because there is no generally applicable rationale for selecting one alternative over the other; rather, the notion of strategies and priorities must be taken into account. As illustrated in Figure 1, the only supportable reason for selecting alternative 6 over 5 is that reducing impact A is more important than reducing impact B.

In decision analysis, the simplest method for selecting from the non-dominated set is to identify specific limits which either must be met or cannot be exceeded. With the imposition of such constraints, the set of alternatives can be reduced, as shown in Figure 2. This approach mirrors the traditional 'command and control' environmental regulatory model. However, this approach has important limitations when applied to environmental impact and LCA. The most obvious one is that it is almost impossible to establish these limits for every potential impact. Additionally, the figure illustrates a more subtle, and potentially more troubling, limitation. Note that alternative 7 is rejected in favor of

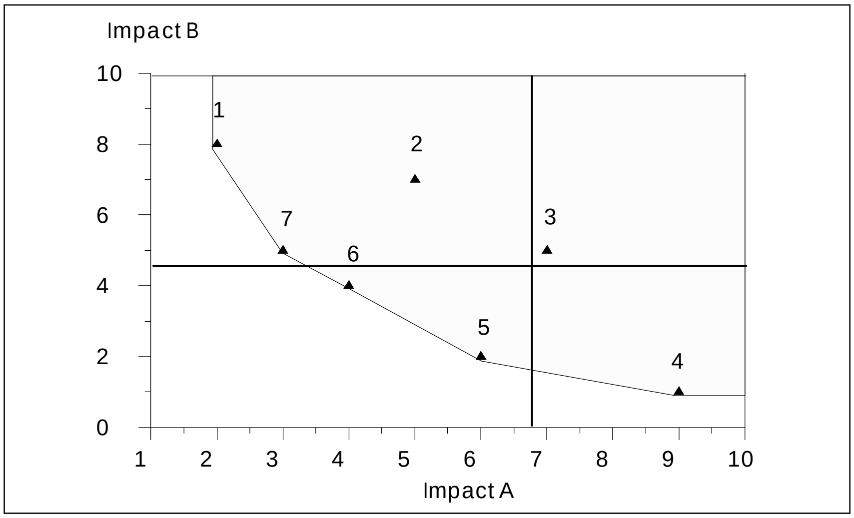

Figure 2: Application of Set Limits or Constraints on Alternatives - Screening

alternative 6, even though the differences in impact B between the two are relatively small in terms of B, while the differences in terms of A are relatively large. Is it really worthwhile to sacrifice the potential gains in terms of A that alternative 7 represents merely because it just fails to meet the fixed limit on impact B?

This limitation of simple constraint-setting (or screening) methods of decision-making is overcome by the introduction of the notion of *value functions*. These functions are representations of preferences among the several attributes which form the basis for the decision (in this case Impacts A and B). The simplest form of a value function is represented in Figure 3a, the linear index. Essentially, a measure of value is estimated by constructing a weighted average of the (two) criteria, and the alternative yielding the best average value is selected. Alternatively, a non-linear value function can also be constructed, as shown in Figure 3b. This value function can represent such observed preference behavior as saturation (i.e., as better levels of one attribute are attained, the incremental value of further improvement is less) and variable rates of transformation among attributes.

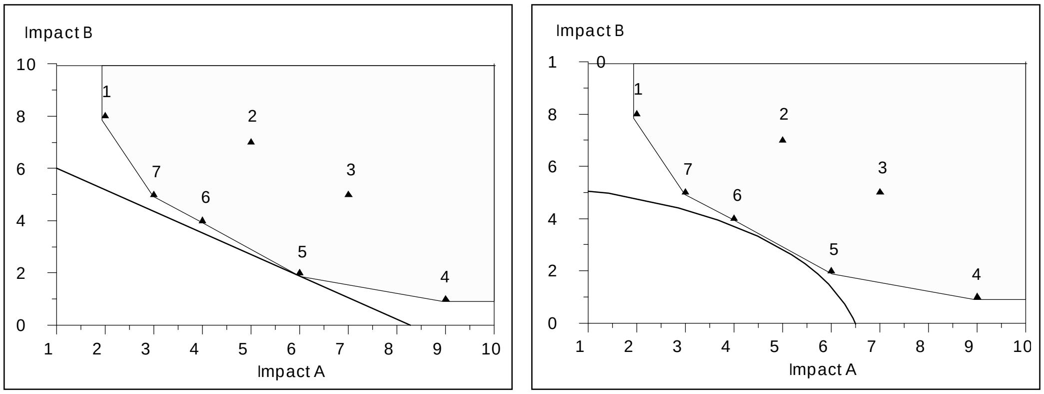

Figure 3a & 3b: Lines of Constant “Value” for Alternative Value Functions

The linear index method is directly analogous to the concept of *monetization*, the transformation of attributes into their dollar equivalents (see, for example, the Swedish Environmental Priority Strategies (EPS) system [4]). The straight line depicted in Figure 3a can then be thought of as a 'budget' for environmental damage. Alternatively, the non-linear preference function methods are direct representations of the consumer economist's classical notion of cardinal utility, where the curved line represents a line of constant utility. The curved line in Figure 3b then represents all combinations of environmental damage from A and B that leave the observer equally well (or poorly) off.

As the figures demonstrate, both of these value functions establish the existence of an alternative that is demonstrably the 'best;' the point of tangency between the line or curve of constant value and the grayed area is the alternative which yields the 'best' combination of characteristics. While the problem of establishing a best alternative in the real world requires the consideration of a much larger set of attributes, the conceptual basis remains the same.

Implications for LCA Improvement Analysis

This review of decision analysis suggests that there are two clear-cut classes of decision problems that users of LCA will face in the final improvement analysis stage of the effort. In one class, the analyst will be confronted with the choice between several alternatives in which one is clearly dominant over the others. This situation is analogous to choosing between an alternative which lies within the gray area in Figure 3 and another which lies on the lower edge of that area; i.e., a choice between a non-dominated and a dominated alternative. In this case, the fact that LCA treats the complete scope of environmental consequences will have exposed the fact that one alternative has better performance in **all** aspects, including the economic and technical areas. For the rational decision maker facing this class of problem, LCA will have unquestionably made the choice easier.

The second class of problems, however, will be much more difficult to resolve. In this situation, the two alternatives which must be chosen between will **both** lie on the lower edge of the gray area; i.e., the choice will be between two non-dominated alternatives. As was shown above, in this situation the analyst alone cannot resolve the problem without the application of some value function, which itself must represent the strategic interests of the community the analyst is attempting to serve.

In these cases, establishing the relevant value functions will be a crucial element of the improvement analysis. For individuals, and probably within many firms, it is possible to develop these functions, using a variety of techniques and structuring the decision problem appropriately [5,6]. Unfortunately, developing such functions for larger and more complex communities is suspect. Conceptually, value functions are based upon the notion of *individual* preference, reflecting strategic objectives. Value functions assume that, given two alternatives, the individual decisionmaker can say one of two things about them: (1) one alternative is better than the other, or (2) both alternatives are equally good.

The assumptions underlying the concept of value functions are particularly weak when the problem of establishing group preferences for environmental attributes is under consideration. There are two reasons for this:

1. In order to choose between two or more alternatives, the implications of the choice must be fully understood. Otherwise, the choice is meaningless, and essentially random. When experts cannot establish what the incremental effect of the potential changes in environmental release and resource consumption represented by two alternatives, it is virtually impossible to expect these experts, not to mention the public at large, to say that one is preferable to the other.

2. Even if all the implications of each choice were completely characterized to the complete satisfaction of all members of the group, there remains the fact that individuals do not have a consistent set of objectives when confronted with environmental choices. For example, some may believe preventing global warming is more important than reducing urban air pollution, while others believe that neither of these objectives is as important as maintaining and improving human health. This lack of a consistent set of priorities in the environmental area essentially eliminates the possibility that a useful value function could be constructed.

While there have been commendable attempts to simplify the enormous detail of inventory data to a representative environmental load, the current practical applications of LCA are purely for internal application, since they are based on their subjective value judgments which are not necessarily supportable in all situations worldwide. The ultimate goals set out by SETAC and the US EPA for improvement analysis based on life cycle inventories are laudable, but can only be realized by some kind of consensus on the values for avoiding environmental degradation.

This suggests that achieving the ultimate stage of LCA will require the development of a basis for devising (and revising) this consensus. In the absence of a common strategic objective, it will be impossible to use LCA to designate ways to achieve environmental improvement beyond straightforward pollution prevention/precautionary principle strategies, because a strategic consensus is required to trade off competing environmental, economic, and engineering goals.

Proposed Methodology

Many of the tools employed to evaluate environmental effects start from an observed release to the environment of some set of effluents or from the consumption of a natural resource. Based upon this observed set of environmental consequences, policies are devised whose goal is to control, limit, or reduce these effects. Missing is the recognition that these environmental effects are the consequence of activities from which an industrial benefit is usually gained. The fact that most environmental impacts are a consequence of activities which also have value cannot be overlooked when analyzing alternative strategies to improve environmental performance.

In order to assure that the connection between industrial activity and environmental consequences is retained and made explicit, the proposed methodology will be based on classical engineering process and economic modeling, focusing upon life cycle issues. The lifecycle paradigm offers an integrating framework for engineering process specific analyses, explicitly linking each step in the production, use, and disposal chain to one another in terms of the products they make, the resources they consume, and the wastes that they generate. By showing how each of these are interrelated, and by basing these interrelationships upon verifiable engineering and economic relationships, a tool of considerable flexibility and power can be developed. In particular, such a framework for analysis will enable decisionmakers to evaluate the consequences of a wide range of technological, economic, and policy changes and to measure these consequences against a set of strategic objectives.

Engineering Process and Economic Modeling

Classical engineering process modeling has been the subject of extensive development within the Materials Systems Laboratory at MIT for the past decade. During this time, elements of engineering process modeling have been married to elements of product design, material properties, and manufacturing assumptions to yield tools for estimating the costs of product manufacture under a wide range of conditions. Such tools have been developed to analyze primary materials production (primary metal extraction, ceramic powder production, and various fiber reinforcements), primary materials processing (metal, polymer, ceramic, and composite product manufacture), component and subassembly manufacture, and end-of-life vehicle processing (e.g., shredding, pyrolysis, and glycolysis). In each case, these tools estimate the costs of production as a function of processing technology, material flows, energy & capital requirements, and operating conditions.

The development and use of these tools has facilitated and extended the scope of analysis of the economic consequences of material, technology, design, and operational changes. They have proven to be particularly valuable at early stages of product development, where they can be used to evaluate the economic implications of materials and design choices, and early in materials processing development, where they have been used to identify critical advantages and limitations of new technologies.

For instance, Figure 4 presents the results of a comparative cost evaluation of several automobile door manufacturing methods, focusing upon material and

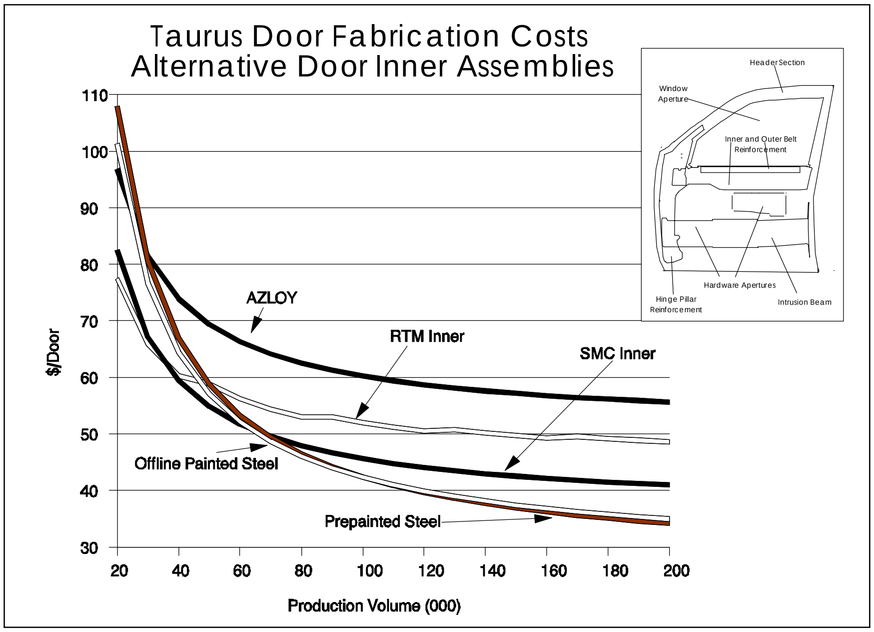

Figure 4: Comparative Costs of Taurus Door Fabrication

design alternatives for door inners. This figure demonstrates that the appropriate technology for manufacturing these inners is a function of vehicle production volume and process technology.

Extending these tools and making them a part of an analysis of environmental impacts provides several benefits:

- First, these tools explicitly consider the technological implications of changes in materials, design, and operating practice. By making these models the analytical heart of the methodology, the technological context within which environmental strategy must be developed becomes an integral part of the decision making process.
- Second, these models also explicitly consider and reveal the economic consequences of these technological changes. Thus, these tools not only provide a technological context for decisionmaking, but they also bring the cost consequences of technological change to the problem of strategic analysis.

In their present form, these cost models only consider material flows and energy consumption in terms of their economic consequences (e.g., cost of materials or cost of scrap). They can be readily extended to a detailed treatment of all material flows within a set of manufacturing processes, including emissions and resource consumption.

	Energy Consumption	Materials Consumption	Emissions To:			Cost
			Air	Land	Water	
	Electrical Coal Nat.Gas	Steel Aluminum Platinum	CO2 NOx HC	Landfill		Manufacturing Vehicle Use Disposal Recycling
(1) Base Case (Steel) Vehicle						
(2) Aluminum Unibody						
(3) Aluminum Space Frame						
(4) Steel Space Frame/ SMC Body Panels						
(5) Aluminum Space Frame/ RIM Body Panels						
(6) Electric Vehicle/ PB Acid Battery						
(7) Electric Vehicle/ NA-S Battery						
(8) Hybrid Electric Vehicle						
(9) Case (5) w/ Pyrolysis Disposal						

Figure 5: Matrix Framework For Inventory Metrics

A Framework For Analysis

The focus of the LCA research program is the development of a framework for analysis that organizes data obtained from the inventory phase in a form useful for understanding the environmental and economic consequences of strategic alternatives. These include alternative product designs, manufacturing technologies and regulatory policies.

Researchers in the International Motor Vehicle Program at MIT are in the process of developing data on cost, emissions, energy and non-fuel resource consumption, at each stage of the product life cycle, from raw material extraction to disposal or re-use. The 1989 Ford Taurus and the 1989 VW Golf (both steel unibody designs) are used for alternative base cases. Since there are thousands of data points in disaggregate form, the challenge is to aggregate the data in a form useful for decisionmakers without losing crucial information. Figure 5 shows one way of presenting the data by aggregating across stages of the product life cycle.

Using technology-based models of the processes employed in the manufacturing of the automobile, a dynamic life cycle inventory can be developed for strategic alternatives. Some proposed cases are shown in Figure 5. Comparing the emissions, costs, and resource metrics for the base case and a light weight vehicle, such as an aluminum unibody vehicle, will not lead to a clear winner. The manufacturing cost of the aluminum design will be higher and energy use during the vehicle use stage will be less. The matrix approach, while leaving each of the metrics in its own units of measure, allows one to explicitly identify trade-offs. The framework can thus serve as a basis for choosing among alternatives as a vehicle for negotiation among parties with different strategic objectives.

Summary

Life cycle analysis is a technique that has already shown great promise for improving our understanding of the wider implications and relationships that must be taken into consideration when incorporating environmental concerns into technical decisionmaking. As these concepts diffuse into industrial and technical decisionmaking, LCA will enable industry and government to find ways to be both more efficient and less harmful to the environment.

However, practitioners and proponents must guard against using LCA to determine “best” modes of action when the consequences of the alternatives expose conflicting objectives and values within the group of decisionmakers. In these cases, no amount of analysis will directly resolve the conflict. Rather, the role of LCA should be to clearly articulate the consequences of each alternative, and to provide a framework for the necessary negotiations.

Of the variety of techniques that have been proposed to integrate environmental knowledge and data into a framework for action, the field of life cycle analysis has emerged as one of the more promising approaches. The life cycle paradigm requires that consideration must be given not only to the immediate impacts of a product or process choice, but also to the products and processes that gave rise to that choice and to the products and processes that occur in response to that choice. For example, according to the life cycle paradigm, it is insufficient to consider the use of steel or aluminum in an automobile solely on the basis the material’s impact upon the weight (and thus the fuel efficiency) of the automobile. Rather, the energy required to extract, refine, process, recycle, and dispose of the vehicle must be considered as a whole. This view reflects the notion that, just like the natural ecology, the ‘industrial ecology’ is a vast network of interconnected activities where the size of a change is no indicator of the scope of its effect and care must be taken to eschew local optima in favor of global optima.

The crucial feature of value functions is that they are a reflection of preference, not only for different levels of performance, but also between different measures of performance. These preferences are a reflection of *strategic* intent, insofar as they indicate the relative importance of different attributes. The fact that differences exist is not a reflection of “irrational” decisionmaking; rather, it is a demonstration that the strategic objectives of different actors can (and do) vary among them. To draw on an example from engineering, it is a fact that the connecting rod of the Ford Escort is composed of forged powdered iron, while the connecting rod of the Acura NSX is composed of titanium. However, the fact of this difference is not a reflection of irrational design — rather, it demonstrates that the design goals for the Escort are different than those of the NSX.

Thus, the effort to identify and characterize the value functions of decisionmakers is actually an effort to understand the strategic objectives of these decisionmakers, and to summarize these objectives in terms of the willingness of these decisionmakers to trade-off one set of attribute values for another. Without such a characterization, it is not possible to distinguish between members of the non-dominated set of alternatives. Clearly, such tradeoffs do occur, since choice among alternatives does take place. The question thus becomes, can these value functions be characterized in advance of a strategic choice, so that the ‘best’ alternative from the non-dominated set can be identified without directly consulting the decisionmaker each time the choice arises?

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Recycling of US Automobile Materials: A Conundrum for Advanced Materials

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Based on materials presented to the 1991 International ATA Conference, June 5-7, 1991

Abstract

This paper discusses the difficulties associated with imposing recycling imperatives upon advanced materials development by examining the case of automotive materials substitution and its impacts upon the recyclability of the automobile. Parallels are drawn between today's issues, which focus upon the recyclability of the increasing polymeric fraction in automobile shredder fluff, and the junked automobile problem of the 1960's, when the problem of abandoned automobiles became a part of the environmental and legislative agenda in the US and overseas.

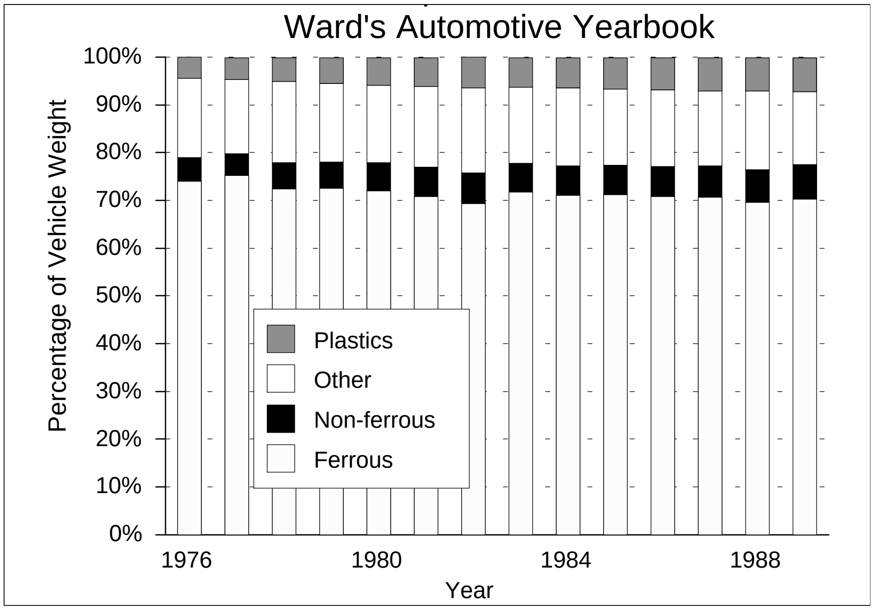
In the 1960's, both the source and the resolution of the junk automobile problem arose through a confluence of technological and economic factors, rather than through any set of regulatory influences. The rise of electric arc furnace steelmaking and the development of the automobile shredder were sufficient to virtually eliminate the problem - so much so that today's problems are incorrectly viewed as novelties.

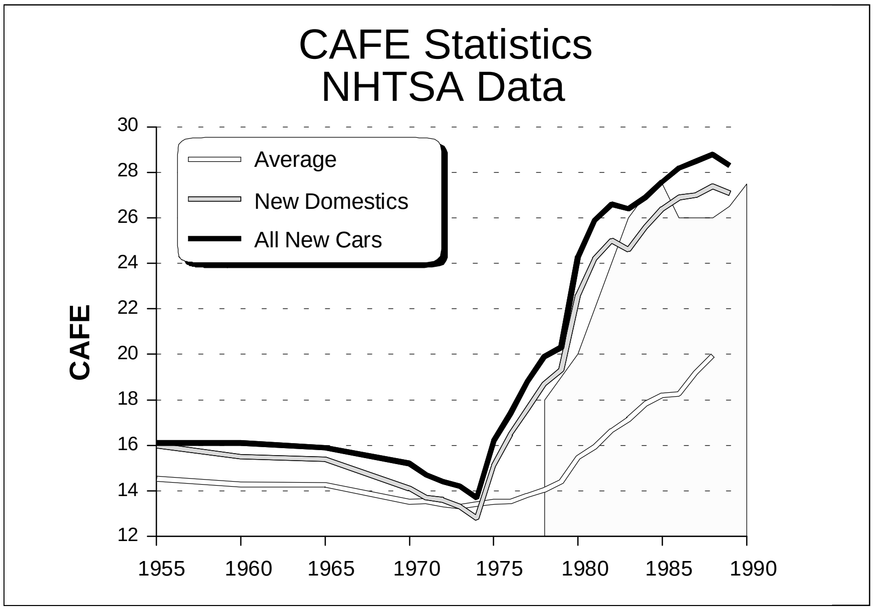
Today's automobile recycling problem again derives from technological and economic factors, but the influences of regulations upon both the source and the resolution of this problem are far stronger today. While there is no lack of technological solutions to the problem of automobile shredder fluff, none yet provides scrap processors with the kind of profit opportunity necessary to implement them. In some ways, it is implicit in advanced materials markets that there is little to no demand for recycled forms of these materials, and, in the absence of these markets, there are few reasons to expect that the solution to today's problems will be achieved as neatly as the last time.

For many years, the question of automobile use has been inextricably intertwined with its environmental impacts. In the United States, a wide range of regulatory requirements link automotive performance and environmental impact. Premier among these are fuel economy standards, which establish efficiency guidelines, and emission standards, which attempt to control air quality. In other parts of the world, there are environmental regulations which mirror the essentially regulatory US model, as well as are those systems which employ market forces by imposing user fees upon elements of automobile performance or design. Some of these systems also bring the market into play through the pricing and taxing of fuels.

After a three to five year lull in US governmental attention to automotive impacts upon the environment, there has been an upswing of activity. While the activity in the traditional areas of emission and fuel economy standards has been well publicized, there also is activity in other, related areas of environmental policy. The impact of the automobile at the end of its service life is beginning to receive attention. The nascent European Community is currently in the forefront of this area of policy activity, and several member states already have legislation on the books that could be used to enforce a wide range of vehicle recycling policies. In response, some European automobile manufacturers have already taken steps to meet this challenge, with BMW and Volkswagen already committed to brick and mortar investment in automobile recycling facilities [1], and Daimler-Benz has announced plans to reuse and recycle a large number of components [2]. These facilities are being built in response to the expectation that, within the next decade, automakers will be responsible for the environmentally sound disposal of their own products. In fact, there already is legislation on the books which could hold German manufacturers to this standard [3].

The spate of interest in automobile recycling is a direct consequence of material innovations in the automobile. Automakers, in response to both market and regulatory pressures, have worked to develop more efficient, lighter weight vehicles that are cost effective and competitive. This has led to both a reduction in



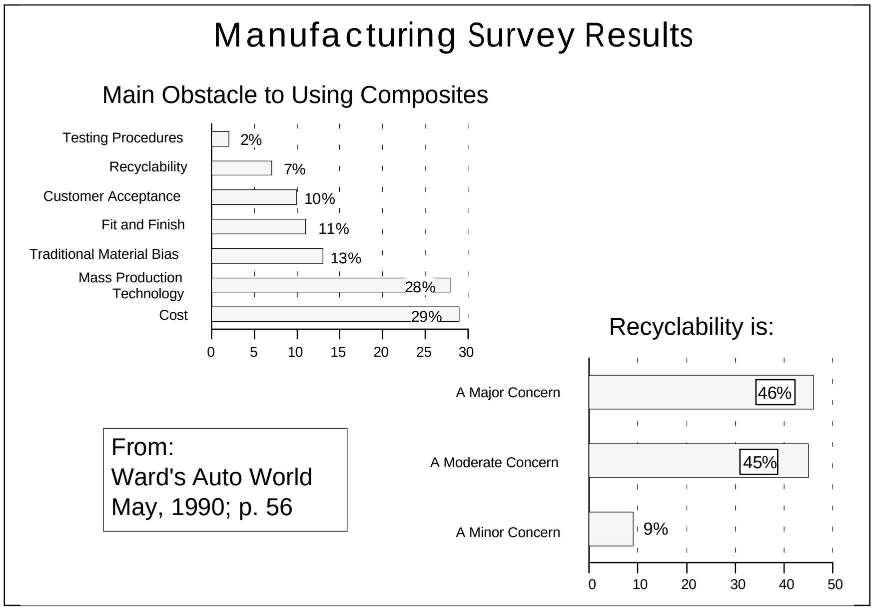


the size of the automobile (a strategy known as downsizing) and a change in the materials used in the vehicle. While all suppliers to the automobile industry have contributed to these goals, the steel and polymer suppliers, in conjunction with the OEM's, are primarily responsible for the weight reductions achieved.

Weight reduction has been one of the major drivers of the automotive polymer and polymer composite industry, and the gains in this area have been impressive. Starting with zinc die castings, the polymer companies have identified target areas in the automobile where either the economics, formability, or weight reducing features of their products have made them the best material for the application. Today, automotive interiors stand in mute testimony to their success. And automobile exteriors have become the current battlefield, with structural applications looming.

The US steel industry, in many respects, was drawn unwillingly into the weight reduction fray, but has responded not only by improving their base material, but also by introducing material innovations of their own. Primary among these have been coated steel sheets, which carry a protective coating that retards corrosion, and high strength steels, which afford comparable strengths at reduced weights.

The increasing polymer fraction in the automobile (and the concomitant decline in the ferrous metal fraction) has enabled automakers to meet their product goals of reduced vehicle weight and improved fuel economy. However, it has also spawned a new environmental problem, whose dimensions are incompletely understood. The automobile, as a major consumer durable, is composed of a large fraction of the materials consumed in industry. As the plastic content of the automobile has grown, observers have begun to question what will ultimately happen to these materials. The thermoplastic polymer suppliers (most notably General Electric) have been asking this question for many years, implying that thermoplastic materials have a recycling advantage over the more popular thermoset materials being used in the automobile. However, it is not all that apparent that even automotive thermoplastics can be effectively recycled, especially if they have either been painted or reinforced with other materials.



From:
Ward's Auto World
May, 1990; p. 56

A recent manufacturers' survey of composite materials use published in *Ward's Auto World* ranks recyclability sixth in a list of obstacles to the use of composite materials. However, there was almost universal agreement that recyclability was a real concern that could impede the use of these materials [4].

Of course, recyclability is a peculiar characteristic to expect of an advanced material like composites. There are very real reasons why such materials almost always are viewed as "unrecyclable." First, an advanced material is usually the product of a sophisticated manufacturing process, which is usually difficult and expensive to undo. Consider, for example, the difficulty of trying to restore an epoxy-carbon fiber composite to its constituent elements for reuse. Second, where advanced materials are employed, they have been specified because of the performance that they provide. The performance of such materials cannot be matched by other materials, including recycled material. Finally, the volume of advanced materials entering the recycle stream is so small that there are few, if any, economic incentives to develop the necessary recycling infrastructure. In summary, advanced materials recycling is usually an expensive proposition, yielding a product whose market cannot support the prices necessary to develop the business.

Nevertheless, recycling concerns have added a new dimension to the materials substitution battles being fought today. The influence of recyclability upon materials choice has been small, by and large, but it has the potential to be decisive. For example, some have suggested that General Motors' use of thermoplastic resins for their new Saturn subcompact is a consequence of Tennessee's refusal to give them the landfill space that the use of more conventional thermoset systems would require. Because GM will be manufacturing these body panels on site, disposal of process scrap and part offal will be a direct cost of manufacturing to them. On the other hand, GM's new All Purpose Vans (APVs), all of whose body panels are plastic, employ nothing but thermoset systems - sheet molding compound (a glass reinforced polyester) and reaction injection molded polyurea. In this case, GM purchases these parts from other suppliers, who bear the process scrap disposal costs.

Whatever the reason, the decision to use advanced polymers in automotive applications is being influenced by questions of recyclability. At the same time, government institutions are beginning to take a direct look at the impact of polymers upon automobile recyclability. A potential collision of policies and economics looms with this confluence of interest, and it is likely to fuel a strenuous debate within not only the automobile industry, but also within the broader environmental and governmental community. For example, recycling issues were a major component of the recent Society of Automotive Engineers Conference in Detroit, both in the technical sessions and on the exposition floor [5].

The irony here is considerable. The automobile industry has worked to meet regulatory goals within the framework of an increasingly competitive marketplace. In so doing, their suppliers have worked with them to develop cost effective, reliable, and attractive products composed of, in some cases, some extremely sophisticated materials. Furthermore, these suppliers have made not inconsiderable research and development outlays themselves, not only to develop new materials, but also new fabrication and production processes. And now, poised on the brink of major commitments to advanced materials, a new set of problems have been proposed.

Of course, the question of automobile recyclability is not a new problem. Twenty-five years ago, the United States was beginning to realize that a burgeoning automobile industry, based at least in part upon elements of Sloan-inspired planned obsolescence, was leading to a rapid growth in the stock of “deregistered” (i.e., no longer registered) automobiles. This fact became increasingly evident as automobiles were discarded, sometimes in very visible locations. As a consequence, the question of what to do about junk automobiles became a question for the national agenda. In fact, in his environmental message to Congress of 2 February 1970, President Nixon stated a concern about the junked auto problem, and called for some system to promote scrapping of junk automobiles [6].

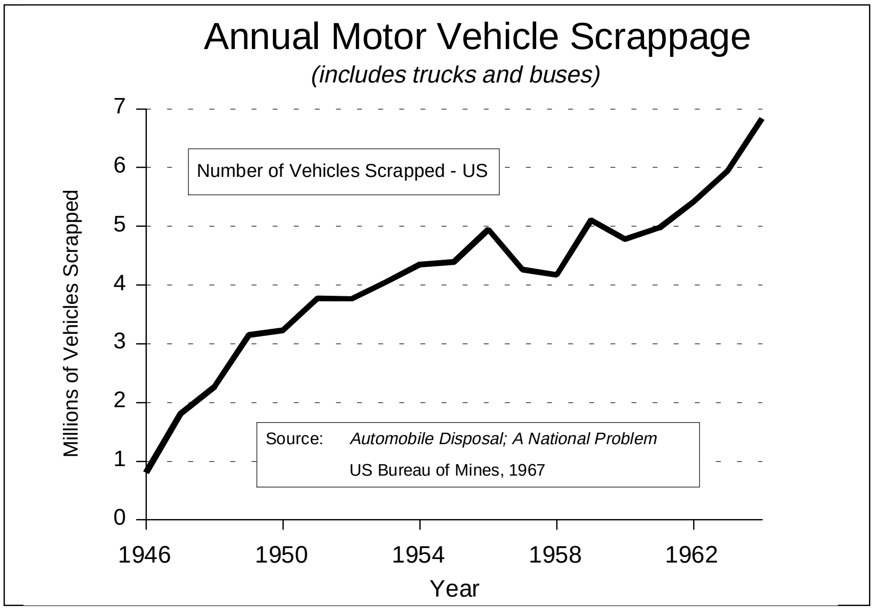
The resolution of that problem has been so successful that the “question” of automobile recycling has been unconsidered for years. This success has been so thorough that today’s problems are being presented as if automobile recyclability were a brand new problem. In fact, many elements of today’s problems directly parallel those of the late 1960’s and early 1970’s, and their resolution informs the polymer recycling problem today.

This paper will discuss the 1970’s automobile recycling problem, and its resolution. Following this historical evaluation, the automobile recycling problem of today will be presented, and some of the potential resolutions will then be presented and evaluated.

Automobile Recycling 1970’s: The Problem

The Bureau of Mines report *Automobile Disposal, A National Problem* [7] opens with a set of statistics to illustrate just how fast the problem of junk cars had grown. Starting with post-World War II data, the figures show that in less than twenty years the number of cars being scrapped had grown by more than a factor of eight, an annual growth rate of almost 12%.

This rapid growth in automobile use and production led to an ugly consequence; the proliferation of junked automobiles. And “ugly” was apparently an

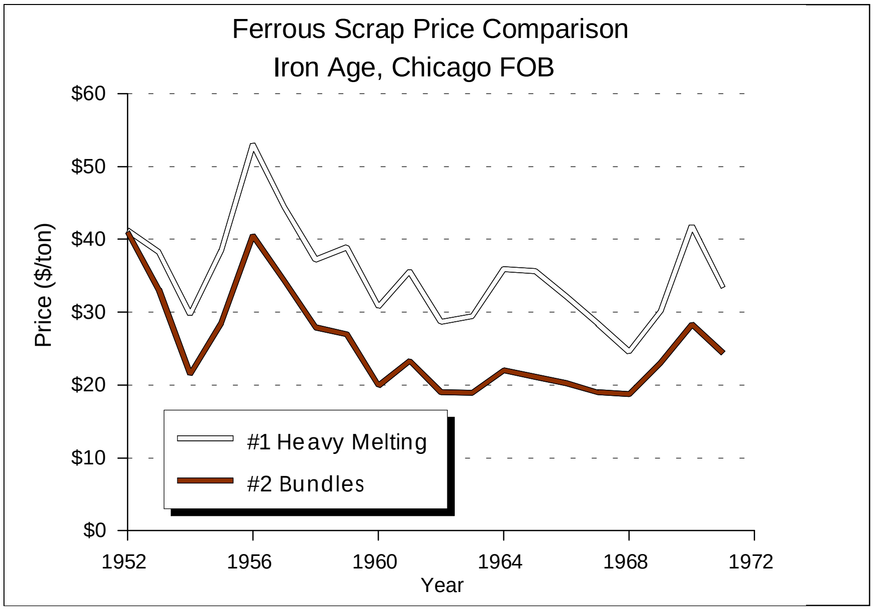


apt description; the early literature of the period characterizes the negative influences of the automobile recycling problem almost exclusively in terms of esthetic problems. Naturally, these esthetic effects did have economic consequences, primarily upon property values. It is illustrative to quote a typical description of the problem:

> Not unlike the "air pollution problem," the production and sale of automobiles give rise to the unsightliness or ugliness attendant with junk yards, to certain social problems arising with respect to abandoned cars and junk yards, to costs for removing and disposing of abandoned automobiles, etc.... Since those people exposed to this unsightliness or suffering from other ill-effects would prefer not to experience these impacts and probably would pay something to avoid it,... the disutility of junk yards and the costs of abandonment and disposal (net of scrap and spare parts value) largely represent external costs associated with automobile production and sales. [8]

Note the parallel drawn between air pollution and the junk car problem. Just as the health effects of air pollution were not raised until later in the debate, the energy efficiency aspects of the junk car problem were largely ignored until the mid-1970's.

Most studies of the problem focused upon the junk car problem as a consequence of a market deficiency; namely, that both the recovery infrastructure of, and the market for, junk cars was inefficient and inadequate. The auto reuse system is composed of four sectors: the auto owner, the auto wrecker, the scrap processor, and the steel mill. Under ideal situations, the auto owner, holding a vehicle which no longer provides reliable transportation, negotiates a price with an auto wrecker. The auto wrecker should be willing to pay for the car because he can find a market for the used parts. Once all useful parts have been stripped from the car, the wrecker removes combustible materials and large components that can be sold for scrap (like the engine block, transmission housing, radiator, and, more recently, the catalytic converter) in preparation for selling the hulk to a scrap processor. This scrap processor further separates non-ferrous materials



from the hulk, which he then sells to a steel mill or a steel foundry to make steel product [9].

Unfortunately, this idealized system was subject to a large number of failings, any one of which meant that automobile hulks were left standing. These failings fell into several categories, and were the consequences of a variety of market factors.

The dominant factor was the price that steel mills were willing to pay for automobile-derived steel scrap. Such scrap was referred to as “No. 2 bundles” or “No. 2 Heavy Melting Steel.” Although there is some confusion regarding the content of bundles, bales, and other scrap designations [10], the critical element of the descriptor is the term “No. 2” scrap, meaning all obsolete steel scrap (i.e., derived from reprocessed steel goods rather than prompt industrial scrap). The connotation is that “No. 2” scrap is not as clean as “No. 1” scrap and, thus, is more difficult to process [11]. The major limitation of using No. 2 scrap were the metallic impurities which would be especially difficult to remove from the molten steel solution, the so-called “tramp elements.” These tramp elements would result in low quality, difficult to form steels, and steel makers were usually unwilling to accept any bundles that could not be checked themselves [For example, see 12]. These concerns were reflected in the price differential between No. 1 heavy melting scrap and No. 2 bundles.

Of primary concern to steelmakers was the copper content of No. 2 bundles. However, there actually are five major elements which must be controlled in order to produce drawing quality steels, i.e., steels that can be used to make automobiles. The then-acceptable upper limits for impurities were as follows [11]:

Element	Upper Limit Weight Percent
Copper	0.09%
Chromium	0.04%
Molybdenum	0.01%
Nickel	0.04%
Tin	0.01%

Comparison with the metals content of a typical disposal vehicles from the 1967 Bureau of Mines report illustrates why stripping of a hulk is such a critical determinant of the economic utility of a "junk car" [7].

Materials Content (lb)	1954 Chevrolet	%	1956 Buick	%
Total Ferrous	27.26	96.99%	3,705.00	94.30%
Radiator	19.60		31.00	
Heater	3.50		6.04	
Battery Cables	1.35		1.17	
Starter	3.39		2.33	
Other	7.27		11.91	
Total Copper	35.11	1.25%	52.45	1.34%
Lead Battery	32.00		37.00	
Aluminum	8.00	0.28%	47.90	1.22%
Zinc Die Castings	41.50	1.48%	123.40	3.14%
Combustibles	278.76		314.90	
Glass	84.50		87.40	
Grand Total	3,205.87		4,368.05	
% Basis (*)	2,810.61	100.00%	3,928.75	100.00%

* Percentages by weight, net of combustibles, glass, and lead battery

As this table shows, the wrecker and the scrap processor must reduce the fraction of tramp elements if the scrap car is to be sold. On one hand, removal of the lead battery and the major copper parts (e.g., the cooling system) is relatively easy; on the other, the engine block and major transmission components can also be easily removed, worsening the tramp weight percentages.

Almost all steelmaking operations make use of steel scrap in order to improve the economics of steelmaking. The late 1960's, however, saw the transition from open hearth steelmaking to the use of the basic oxygen furnace (BOF). The BOF process is technically superior to that of the open hearth, but the change depressed the market for steel scrap because the amount of steel scrap that could be charged to the BOF was less than could be charged to the open hearth furnace. Typical values are about 45% scrap in an open hearth charge versus 28% in a BOF charge [13]. However, another steelmaking technology, the electric arc furnace (EAF), was on the rise. This process could use an almost 100% scrap charge, and was particularly suited to the fabrication of alloy steels. However, because it accounted for only a small fraction of the market, and was devoted to fabricating specialty alloys, its demand for the relatively low quality automotive scrap was small.

Thus, the market for automobile scrap was softening, and the value received by either the auto owner or the scrap processor was small. In fact, a survey of Connecticut scrap processors published in 1969 suggested that many auto wreckers charged auto owners to take their cars, while at the same time it was too expensive to strip them so that they could be sold to scrap processors [14].

Preparing a vehicle hulk for a scrap processor essentially involves removing any remaining non-ferrous parts and removing non-metallic components, like glass, hoses, tires, and upholstery. In many cases, wreckers would hire crews of workers to strip the non-ferrous metallic parts from a set of hulks, which would then be set ablaze to get rid of the remaining non-metallic components [7]. As clean air regulations and burning bans began to be implemented on a local level (especially urban areas), this economical method for removing non-metallics was taken away from auto wreckers, further increasing their operating costs and, thus, reducing the value of junk cars to them [14].

As a consequence, automobiles were being abandoned on public roads, dumped in out-of-the-way lots, accumulating in wrecker yards, and potentially ending up in auto graveyards. The Bureau of Mines study found a broad spectrum of graveyards, ranging from well-organized adjuncts to auto wrecker yards to rural dumps for non-functional cars. The common element of these graveyards was that the cars found there were not part of the recycle stream, but were instead left there to rust because it was not worthwhile to do anything else with them [7].

Automobile Recycling 1970's: Resolution of the Problem

The literature of the junk car problem also proposed a variety of solutions to the problem. These ranged from a purely economic argument, suggesting that the junk car problem was merely a question of internalizing a troublesome market externality [8], to a detailed set of potential regulatory and legislative steps to be taken. The latter list is instructive, since many of the ideas presented then have resurfaced in the current problem.

The Cornell report [9] essentially divided the potential intervention mechanisms into two groups, charge mechanisms or payment mechanisms. Charge mechanisms collect funds from users for one of two purposes; either to underwrite recycling efforts or to provide economic incentives to use less pernicious alternatives. Payment mechanisms are designed to promote the flow of junk cars through the recycle stream by offering financial incentives.

The four charge mechanisms considered most desirable were:

1. Charges paid at new vehicle purchase - The Cornell study proposed that these charges could be a simple flat fee, a fee based upon income surrogates like vehicle price or horsepower, or a fee based upon the estimated dismantling cost of the vehicle.
2. Annual charges paid with registration fees - This again could be a flat fee, or it could be based upon vehicle age.
3. Embedding the charge in the gasoline tax - Here the fee would be based upon vehicle use, although the economic incentive would be lost since the apportionment of the tax would be invisible.
4. Charges against general revenues - While this would be simple, it would charge people who do not own vehicles, and who therefore do not contribute to the problem.

Additionally, charges could be imposed as penalties upon those who hinder vehicle recycling. These charges could either be levied against autowreckers who take too long to pass their hulks on to scrap processors or against those who abandon vehicles.

The list of payment mechanisms is somewhat more limited and essentially suggests that the payment system be set up to pay a fee to participants in vehicle hulk transactions, especially the transactions between the auto wrecker and the scrap processor. This mechanism would essentially pay one or both of the participants cash for each hulk added to the recycle stream.

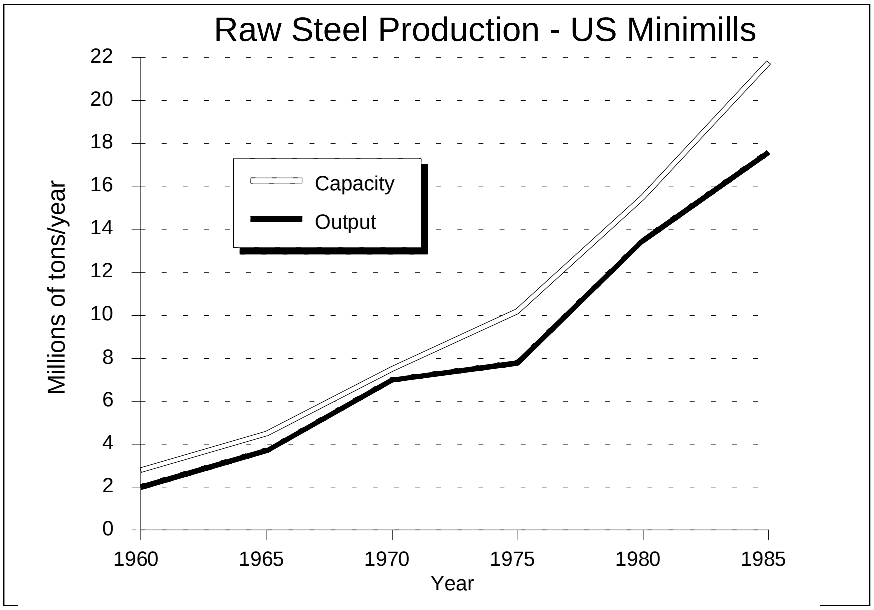
It is interesting is to note that while several of these mechanisms became part of proposed legislation, none of them passed. (This is in contrast to Norway and Sweden, where vehicle recycling mechanisms and fees were legislated. See Reference 15.) The Motor Vehicle Disposal Act (S 3522, 1970) would have required that all registered vehicle be affixed with a tag indicating that a fee had been paid into a deposit fund. This fee would then be redeemed by the processor who recycled the vehicle. The Junked Auto Disposal Act (S 3400, 1966) would have taxed all new vehicles to fund recycling. Other bills which would have promoted the development of recycling at the state level were also proposed.

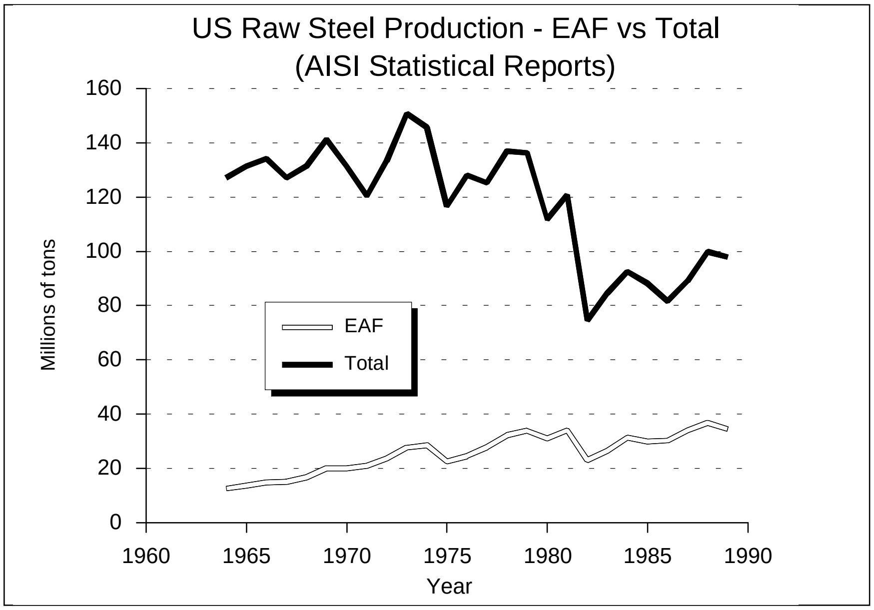
However, the resolution of the junk car problem was not found within legislatures or regulatory committees. Instead, it was a confluence of two technologies and one market event which transformed the junk car from an eyesore into a material resource.

The first of the two technologies has already been mentioned, the electric arc furnace. Even by 1967, spokesmen for the electric arc furnace industry were predicting that “the electric furnace will virtually monopolize the melting of scrap” and that “scrap preparation will be aimed at electric furnace use ”[16]. And, in fact, the growth of the electric furnace segment of the steel industry has been dramatic. The following figures show the rate of growth of the so-called minimill segment of the industry.

The reasons for this growth are manifold. Unlike the BOF, the EAF can operate at a relatively smaller scale, so the capital costs of entry are lower. An early specialization in low diameter products (e.g., wire and reinforcing bar) and locating near scrap supplies and markets gave them a transportation advantage that could be exploited.

As the technology was refined, diversification into more sophisticated products placed the minimills in direct competition with the large integrated steelmakers. Specialization at the plant level enabled the minimills to target particular markets and to achieve production economies that the diversified producers

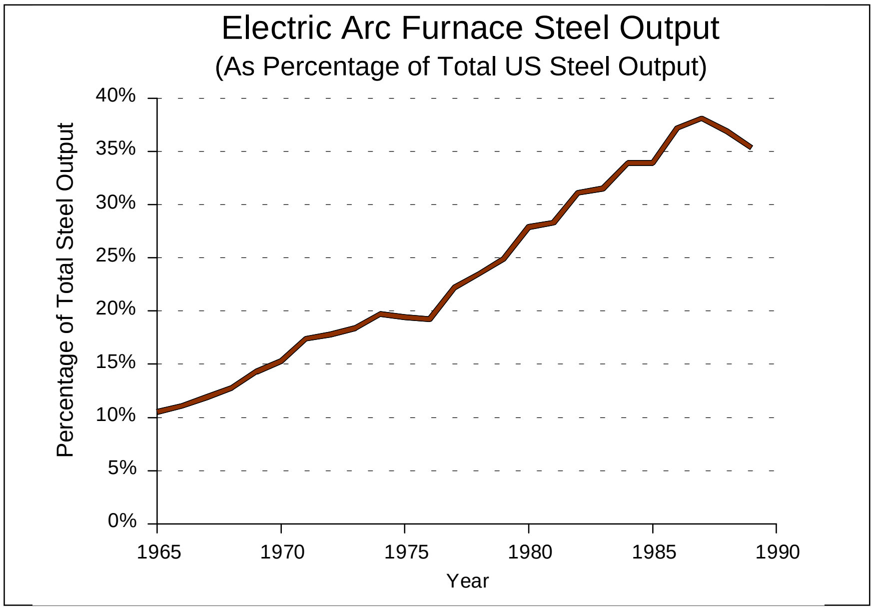


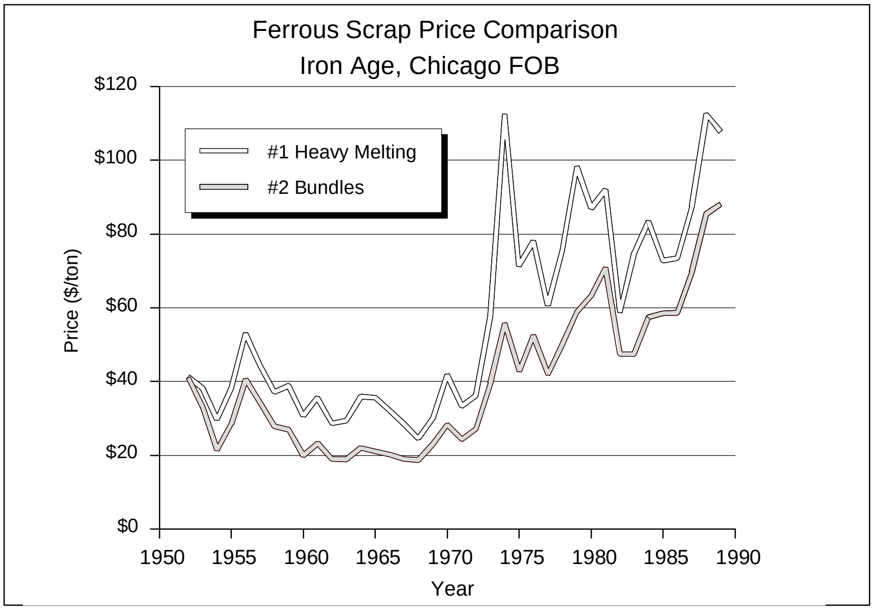


could not match. And, finally, their access to low cost raw materials (steel scrap) enabled them to produce steel at far lower costs than the integrated producers [17].

As the growth of the minimill suggests, the price of scrap steel has remained fairly stable, suggesting that the economic incentives for junk car recycling did not change over this period. While this is generally true, there was a spike in scrap steel demand during 1973-74.

During this period, there was an unprecedented confluence of demand for all materials, as several industrial economies peaked at the same time. Mill operating rates were near or at capacity, and there was a shortage of finished steel. In order to meet orders, the large mills found that, in the absence of iron ore, they had to enter the scrap market. Their arrival, joined by the startup of several new electric furnaces, increased the demand for scrap steel. The first oil shock, and

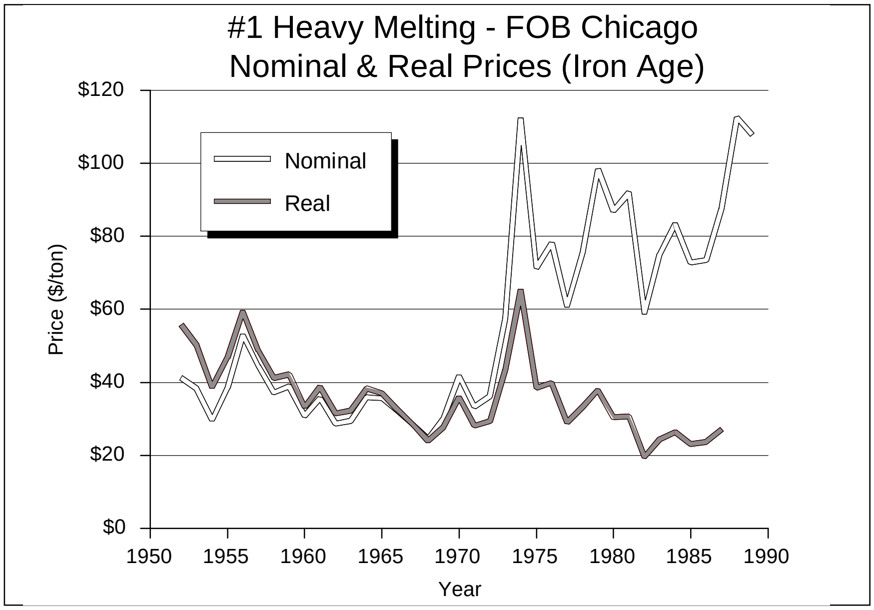




its attendant repercussions, led to a speculative fever in almost all raw materials, which was initially limited through the imposition of price controls from mid-1973 and the control of overseas export of industrial scrap. However, during early 1974, the price controls on industrial scrap were lifted and the price of scrap skyrocketed [18].

However, except for the events of 1973-74, the price of steel scrap has remained fairly stable. When inflation is taken into account, the real price of steel scrap has changed little, absent the 1973 runup in price [17]. The following figure illustrates the point well.

The final element of this transformation of junk into resource was another technological development, although a somewhat more prosaic one. This element was the development of the automobile shredder, and the associated separations technologies it made feasible. As was described above, most automobile hulks were delivered as bundles or bales, usually contaminated with tramp elements.



The presence of these tramp elements could be traced back to the fact that it was uneconomical to hand strip the auto hulk of components made of these tramp elements. (In fact, in today's automobile assembly plants, if the wrong wiring harness is installed in a finished car, it is frequently cheaper to sell the car for scrap than to try to remove and replace the harness.) What was needed was a less expensive way to separate the steel from the rest of the automobile.

The machine developed to achieve this goal was the automobile shredder. This machine takes a complete automobile (less tires, radiators, gas tanks, and batteries) and shreds the car into fist-sized pieces. This process stream then passes through a set of air knives to remove non-metallics and magnetic separators to isolate the ferrous fraction. More recent developments include the use of flotation separators to fraction the non-ferrous metals [11,19]. Typical compositions of the non-magnetic fractions of shredder process streams are 2-4% Cu, 1-2%Pb, 6-15% Zn, 0.1-0.2% stainless steel, 6-16% Fe, 20-25% rubber and plastics, 35-50% glass and non-combustible dirt and dust [19].

The primary advantage of a shredder is that it provides a purely mechanical method for reducing the non-ferrous content of automotive scrap. Even as early as 1967, the advantages of shredded scrap over conventional No. 2 bundles were cited:

> With the electric furnace falling heir to the great bulk of scrap, scrap preparation will be aimed at electric furnace use. The fragmentized or shredded scrap that has come on the market in the past few years has proven so advantageous from both a chemical and physical standpoint that the bundle seems doomed to oblivion.... Fragmentized scrap costs more to prepare, but it is worth more. [16]

The contemporaneous Bureau of Mines study [7] was not quite as enthusiastic about shredding, but it did state:

> Some consumers reportedly have been willing to pay premium prices for this product [shredded automotive scrap]. Other customers contended that shredding was not a universal solution to the automotive scrap problem and that scrap of equivalent or better quality can be prepared for their purposes more cheaply by stripping and baling or shearing.

Nevertheless, shredding emerged as the dominant method for the preparation of automotive scrap and, with the extension of its application, led to the rapid demise of the "junk auto problem." By 1977, it was claimed that

> more junk cars have been recycled in the past three years than were retired from service during this time. This has resulted in a reduction in the national inventory of junk cars, and the junk car has become the largest single source of post-consumer scrap - scrap from junked products; some 30 to 40 per cent comes from scrapped cars. More recently, the junk car has emerged as a major source of secondary zinc supply. *Clearly the junked car is the most recyclable and recycled of post-consumer products*. (emphasis added) [20].

Automobile Recycling 1970's: Summary

By the late 1960's, it was clear that the then-standard practice of dumping automobile hulks in so-called "graveyards" would not remain tenable. The space available for such dumping was becoming increasingly scarce and expensive and, more importantly, there was the beginning of an environmental awareness in the form of sheer esthetic distress combined with a concern for secondary economic and environmental effects.

The rationale for automobile dumping was simple; while still-working parts of these dumped automobiles could be resold into the used parts market, the remaining hulk had no economic value and dumping was the sole option available. Public pressure to do something about dumping arose, and a wide range of policy proposals were made.

However, the solution to this problem of automobile recycling was not found in legislative chambers or in committee rooms. Rather, a combination of economic forces and technological development transformed the valueless automobile hulk into a useful material resource. Almost in conjunction with the rise in the number of junked cars came the development of an efficient, small scale steelmaking technology, centered upon the electric arc furnace. This steelmaking technique has many economic advantages, the most important one being its scale. Because EAF steelmaking is a relatively small scale process, the barriers to entry are relatively low and specialization on concentrated product lines is feasible. However, the critical limit to the implementation of electric arc furnace technology is the requirement that a significant fraction of the furnace feeds must be steel scrap, rather than raw ores. The conversion of the large steel mills from open hearth to basic oxygen furnaces represented an opportunity for EAF technology as the demand for, and thus the price of, steel scrap was falling.

The hulk automobile had been used as steel scrap in the past, but the nonferrous fraction made for relatively low grade scrap, which could not be used in high quality steelmaking. In order to use automobile hulks as steelmaking feedstocks, a way to separate the undesirable materials was required. In response to this need, the shredder/magnetic separation process was developed. With this development, what had been a potential economic burden was transformed into a valuable material resource. Shredded automobiles became one of the primary feedstocks of the steel minimill industry, probably the most profitable of steelmaking operations in the US today.

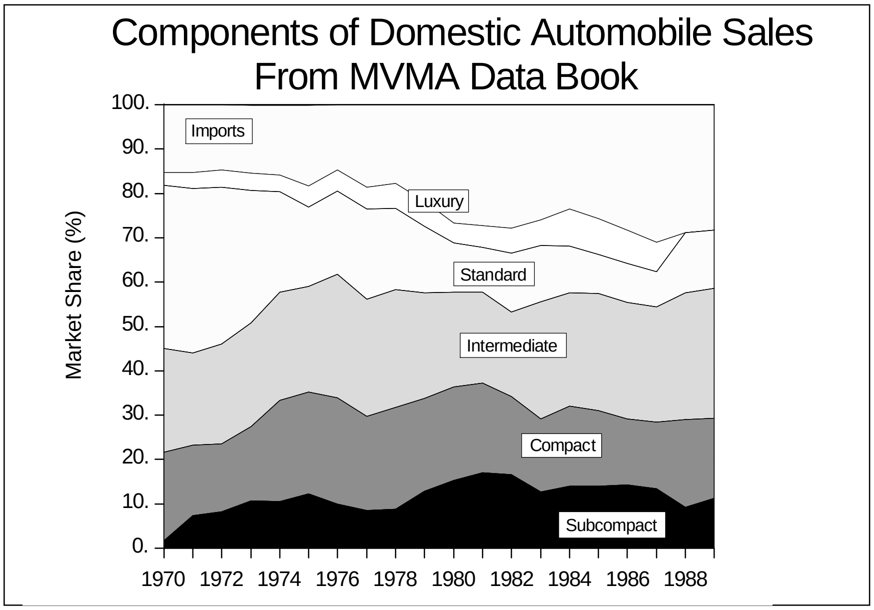
The impact of the steel supply crunch of 1973-74 upon this development is less clear. Certainly the rapid run-up in steel scrap prices helped to rationalize the modernization of scrap processing facilities, with the attendant financial requirement to process as many vehicles as possible. However, the fact that the shredder business continued to grow beyond the price anomalies of this period suggest that the price increases helped to accelerate a development that was inevitable. Certainly, the real price of steel scrap has since fallen to pre-1973 levels, and the current US shredder facilities still number 200 today.

In retrospect, the resolution of this automobile dumping problem seems almost magical. This is perhaps unfortunate, since it perpetuates the dangerous perception that technology will always find a painless solution to any situation, and thus all that is needed is to push technology along through regulatory mandates. As this case shows, while there was much in the way of legislative and regulatory discussion, technological and economic pressures resulted in an efficient solution with essentially no intrusion upon the private sector. The development of a market for, and thus a business opportunity in, shredded steel scrap was sufficient to spur large-scale recycling of what had been viewed as an unattractive, low value automobile hulk.

Automobile Recycling 1990's: The Problem

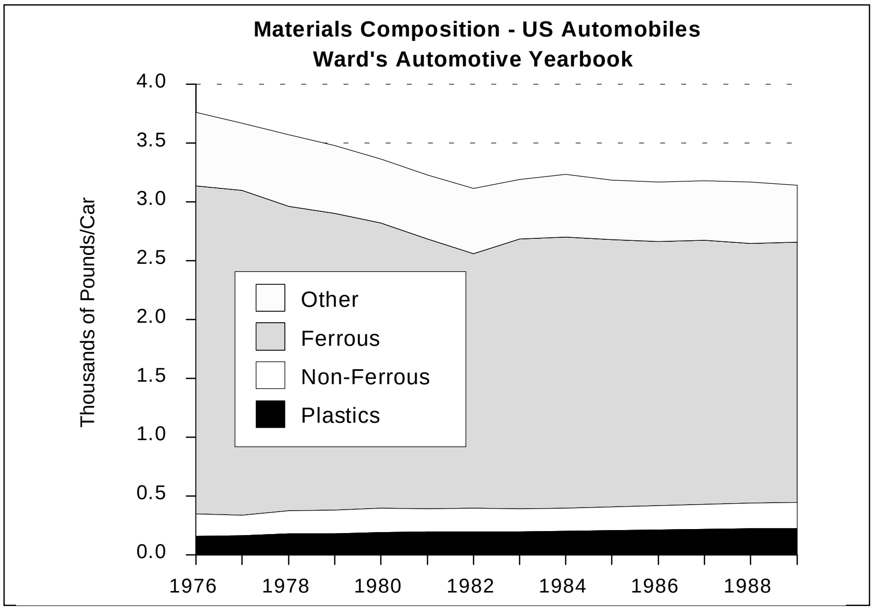
During the 1970's, as the problem of junk car recycling receded, the automobile industry was reacting to two challenges; one competitive and one regulatory. On the regulatory side, emission controls and fuel economy standards challenged the engineering and technological know-how of the automakers. At the same time, the competitive challenge of overseas competition threatened their product design, planning, and manufacturing capacities.

In response, the automakers have embarked upon essentially a two-pronged strategy. With the ultimate goal of vehicle weight reduction, which should both reduce costs and improve fuel economy, both the size and the ferrous metal content of the automobile have been declining, while the number of scrapped cars has continued to climb.



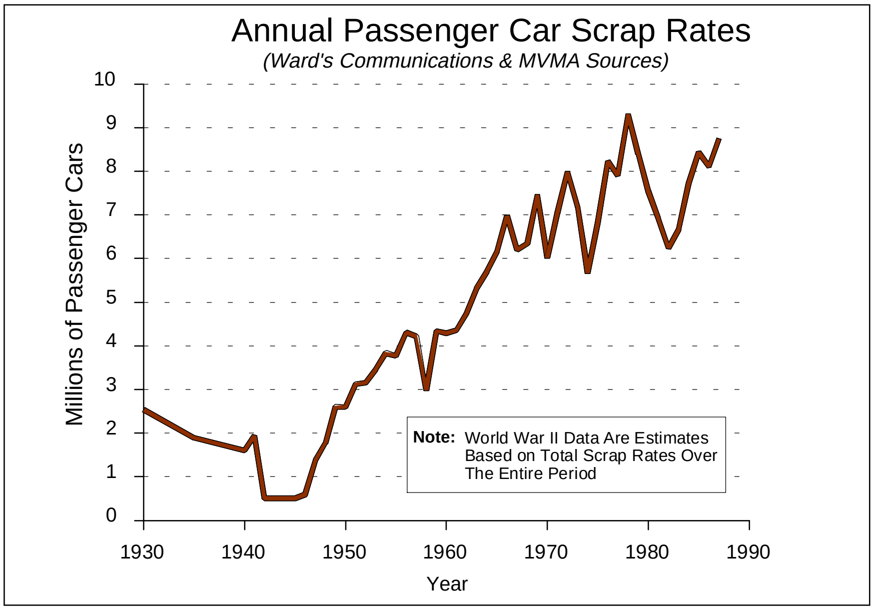
The automobile industry and its suppliers have met with a considerable degree of success in meeting both their regulatory and competitive challenges. Both the downsizing and the materials substitution strategies have achieved their weight reduction and fuel economy goals, and their materials expertise may even afford a degree of competitive advantage in product design, especially in the polymer composites area.

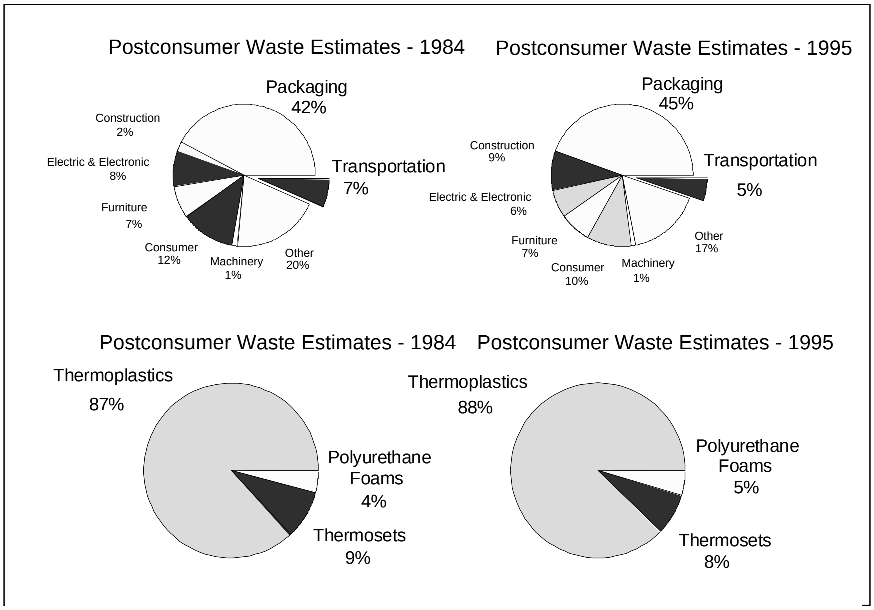
However, it is beginning to appear that the strategies which have been and continue to be used to meet these challenges are in conflict with the recyclability of the automobile. Recent articles in the popular press have suggested that, because no one knows how to recycle composites and polymers, their use will represent an environmental problem in the future [21]. Further, the automobile engineering community is also being presented with pleas to consider recycling during product design, combined with descriptions of the difficulties associated



with plastics recycling, introducing the concept of “design for disassembly” or “design for recycling” [22,23,24,25]. Finally, plastic suppliers are drawing their own battle lines, making claims regarding the relative recyclability of their products while automakers walk a fine line trying to be “good corporate citizens” [21].

However, the real problem is not the recyclability of the polymeric content of the automobile, although it is a contributing element. In fact, the whole question of automobile polymers recycling is something of a red herring, when the entire polymer waste stream is taken into consideration. A review of the literature suggests that the primary source of polymeric waste is packaging, and it is expected to remain so for the near future [26]. Furthermore, when examining the solid waste stream as a whole, paper emerges as a major constituent of landfills [27]





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Recycling industry observers as early as 1980 [28] identified that changes in automobile material content would have an influence upon their recyclability. However, their emphasis was not upon the waste of a potential plastic resource, which has been the primary focus of the current discussion. Instead, their concern has been that the change in automobile material content would ultimately make it uneconomical to recycle the ferrous content of the junk car [29,30].

Upon examination, it is apparent that both elements of the automaker's strategy have reduced the value of, and thus the incentive to recycle, hulk automobiles. Overall weight reduction limits the total amount of material that can be profitably resold from any single vehicle, and the increasing fraction of lightweight non-metallic materials increases the amount of shredder "fluff" which has to be disposed of in a landfill. In fact, because this fluff comprises such a disparate assortment of materials (in particular, lead from automotive scrap and PCB's from electrical capacitors, primarily found in appliance scrap), it runs the risk of being classified in many areas as a hazardous waste, with a concomitant increase in disposal cost [31]. A breakdown of costs reinforces this view [32]:

Typical Hulk Weight	3150 pounds
Steel Scrap: 2250 pounds @ $125.00 net ton	$135.00
Non Ferrous: 150 pounds @ $0.12 per pound	$18.00
Fluff: 750 pounds @ $125 net ton disposal	-$47.00
Freight	-$10.00
Processing Cost: 3150 pounds @ $30 net ton	-$47.00
Scrap Value of Hulk	$48.75

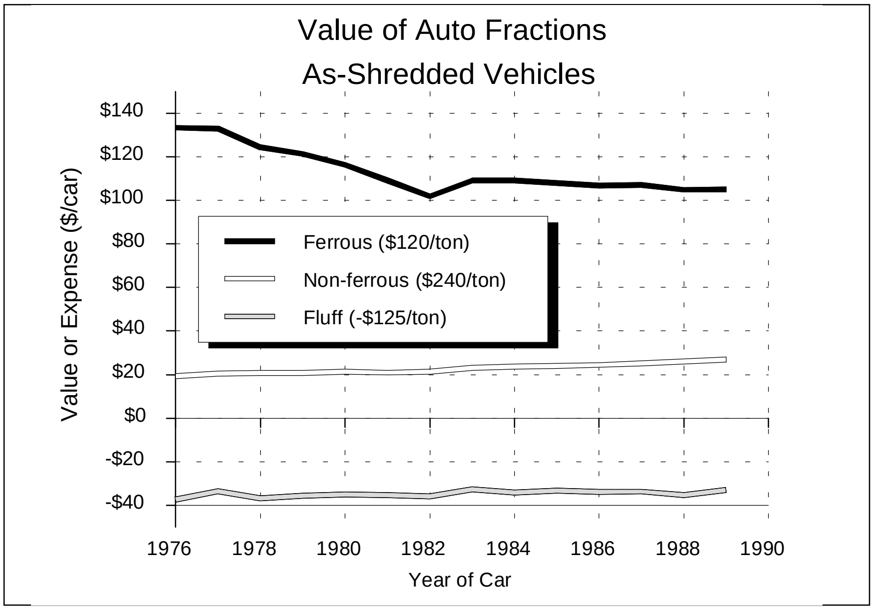
As this breakdown illustrates, as the use of non-traditional, advanced materials in the automobile increases, the overall profitability of, and thus the incentive to, recycle the automobile is endangered. Even though the volume of plastics in society's waste stream is small, the dangers of not addressing the question of plastic recyclability are clear and present. Furthermore, the automobile industry seems to be poised on the edge of making even greater use of these materials, particularly in view of the increasing demands for fuel efficiency that are being made. Some work has been done on a purely speculative basis to evaluate the potential economic consequences of materials substitution on shredder economics, most recently Henstock [30]. His analysis assumed a fairly large substitution of aluminum for ferrous materials, which is an optimistic scenario since no increase in fluff is assumed. Yet, even this analysis was at best indeterminate, although his conclusions suggested that the economics of shredder operation were definitely being challenged.

Based upon the Waxman figures presented above [32] and material content of today's cars, a simplified analysis can be done. The data employed are presented in an Appendix. Assuming that the lead battery and the large iron castings will be separated from the junk car, and that the fluids will be drained, the remaining material contents can be separated into steel scrap, non-ferrous scrap, and fluff. Using Waxman's figures, the economic value of the average car, in constant dollars and assuming fixed operating, transportation, and disposal costs, is as presented below:

Vehicle Year	Steel Scrap	Non-ferrous	Fluff	Process Cost	Freight	Total	% change from 1976
1976	$133.38	$19.38	($37.44)	($44.75)	($10.00)	$60.57	0.00%
1977	$133.05	$20.46	($33.59)	($43.88)	($10.00)	$66.03	9.02%
1978	$124.44	$20.70	($36.75)	($42.52)	($10.00)	$55.87	-7.76%
1979	$121.38	$20.70	($35.59)	($41.48)	($10.00)	$55.01	-9.18%
1980	$116.37	$21.36	($35.03)	($40.17)	($10.00)	$52.53	-13.28%
1981	$109.11	$20.94	($35.44)	($38.40)	($10.00)	$46.21	-23.70%
1982	$101.94	$21.30	($35.88)	($36.76)	($10.00)	$40.61	-32.96%
1983	$109.05	$23.10	($32.84)	($38.03)	($10.00)	$51.27	-15.35%
1984	$109.11	$23.70	($34.13)	($38.43)	($10.00)	$50.26	-17.03%
1985	$108.06	$24.00	($33.38)	($38.03)	($10.00)	$50.66	-16.36%
1986	$106.74	$24.42	($33.81)	($37.85)	($10.00)	$49.50	-18.28%
1987	$107.10	$25.20	($33.75)	($38.03)	($10.00)	$50.53	-16.58%
1988	$104.88	$26.10	($35.41)	($37.98)	($10.00)	$47.59	-21.42%

While this table represents a simplistic analysis, it does illustrate the point that the value of the scrap car is falling as the material content changes. Furthermore, many would say that the table represents an optimistic assessment. It assumes that fluff disposal and shredding and separation costs will remain constant, neither of which is likely to be true. While these assumptions are offset by similar assumptions about the value of non-ferrous scrap and freight costs, it is unlikely that their positive effects would outweigh the likely rapid rise in landfilling costs.

It is important to note that the assumption that steel scrap value will remain fixed was not challenged. This is partly explained by the fact that historical data does not show that scrap prices have increased over time. Interestingly enough, many observers blame export restrictions on scrap for depressing the price of automotive scrap during the mid 1980's [13]. While these restrictions were put in place during the rapid price run-ups of 1973-74, the threat of their application depressed steel scrap prices worldwide, to the advantage of domestic consumers of scrap. Interestingly enough, as the ferrous scrap business has enjoyed strong export business in the past two years, the price of steel scrap has



risen accordingly [33]. However, the price of steel scrap has recently begun to pull back from these levels.

Thus, the problem of automobile recycling being posed today mirrors almost precisely the situation of the late 1960's. While a recycling infrastructure is in place, the reprocessing of the automobile hulk is becoming uneconomical, or at least has the potential to become so. In fact, although it is not as apparent today as it was in the 70's, some charge that backlog of obsolete scrap available for, but not being used in, recycling is growing [13]. Even if scrap backlogs are not growing, there is undeniably a growing backlog of stored shredder fluff. While the recycling of the automobile is still perhaps one of the most profitable recycling businesses, its profitability has begun to suffer, and there are cries of alarm beginning to be heard, both inside and outside of the industry.

Automobile Recycling 1990's: Resolution of the Problem

The resolution of the problem of scrap automobile recycling in the 1990's is likely to stem from the action of many of the same forces that resolved the problem in the 1970's. Premier among these again are technological developments, although economic factors are going to drive these developments. On the other hand, a legislative and regulatory infrastructure has also been established since the 1970's, including the Resource Conservation and Recovery Act of 1976 and others [34,35]. Furthermore, environmental awareness is also making its contribution to the current situation.

While it is not possible to predict exactly how the current problems will be solved, a brief survey of these elements should demonstrate that the situation is not so critical that immediate action is required. Rather, a deliberate evaluation of potential short- and long-term solutions is merited.

Plastics Recycling Technologies

As was illustrated above, the dominant polymeric waste source is packaging materials, while transportation polymeric waste is a small fraction of the stream. It is thus not surprising to find that the bulk of plastic recycling activities have been focused upon this area. The major suppliers of these materials, including duPont, Union Carbide, and Dow Chemical, have participated in a variety of joint ventures to develop and assess technologies for separating and processing plastics in the waste stream, most notably polyethylene terepthalate (PET, the primary constituent of plastic bottles) and high density polyethylene (HDPE, a packaging film and a bottle material) [36,37]. In fact, there already is a market for recycled PET, HDPE, and low density polyethylene (LDPE).

The primary problem for plastics recycling in general is sortation, directly analogous to the hulk stripping problem. If the plastic material can be identified and separated, it probably can be recycled [26]. A wide range of technologies are under development [36,38,39]. Of course, the likelihood of their ultimate use will depend upon the economics of the recycling process and the market for the product that results. Given some of the draconian measures that have already been implemented (e.g., the New Jersey ban on polystyrene containers for McDonald's hamburgers), the plastics industry is as interested as everyone else is in solving the polymer recycling problem [40].

However, the automotive sector is limited by the very fact that it contributes such a small faction of the total waste stream. Furthermore, shredder fluff contains an extremely disparate array of polymeric materials, ranging from PVC upholstery, glass fiber reinforced polyester body panels, and glass filled polyurethanes to some of the most sophisticated engineering resins developed. Because the size of this waste stream is both small and complex, economical recycling options are still being developed.

Even though analyses of shredder fluff streams have been underway for over a decade [41], approaches to handling the shredder fluff stream currently seem to fall into two categories: reduction to combustible form [for example, see 42, 43] or reprocessing to a lower grade polymeric amalgams [for examples, see 36 and 44]. However, there are some technical developments which suggest that there are other opportunities. For example, the automobile interior is already part of the shredder fluff stream. But, because so much of the interior is PVC, it is likely that some of the separation technologies being developed for the packaging waste stream could be employed, whereupon established PVC recycling techniques could then be used [for example, see 45]. Furthermore, recent work suggests that the reuse of RIM polyurethanes and SMCs (both thermoset materials) can be credibly achieved (see, for example, 46, 47, and 48).

Pyrolysis has received a great deal of consideration in the last few years. This technology essentially heats polymeric materials under controlled atmospheres, yielding combustible gases, organic fluids, and char (ash). The energy content of the gases have value, while work is being done to see if the fluid can be fractionated. The char potentially can be used as fillers in making other plastic components. The primary thrust of pyrolysis development has been focused upon tires and SMC, but other automotive polymers are also candidates [49, 50]. Not only the automobile industry and suppliers, but also the scrap industry, through their Institute for Scrap Recycling Industries (ISRI), have been very active in the pursuit of this technology.

In spite of these treatments of the shredder stream, both the automobile companies and their polymer suppliers seem to be approaching their problem as if they expect future automobile wreckers to return to hand stripping of the junk car. For example, General Electric has entered into agreements with European automobile dismantlers to take back GE plastics from junk cars, as well as to set up mobile regrinding operations. On the other hand, BMW is setting up a facility to handle all dismantling of BMW vehicles, whose plastic components will be both labeled and designed for easy disassembly and separation [2, 36]. Finally, the Society of Automotive Engineers has developed a standard labeling system for polymeric components to ease identification of dismantled parts.

While these ventures certainly offer some competitive advantage to the manager of the operation, it is unclear that they will be willing to pay the kind of premium required to justify the return to hand stripping of automobiles. This question is particularly relevant in light of the fact that, as the earlier section of this paper showed, it is the use of the shredder that made automobile recycling economically feasible in the first place. However, in the near term, it may be that hand stripping of large polymeric panels will have to be a part of automobile wrecking and design [22]. For example, Volkswagen and the German automakers association have timed the rates at which plastic components can be hand stripped from current VW vehicles [2].

Economic Drivers

Probably the dominant driver for automotive plastics recycling will be landfill tipping charges. Rightly or wrongly, shredder fluff can be classified as a hazardous waste, with the accompanying limitations upon its disposal. While incineration seems like a credible alternative to landfilling, it turns out that shredder fluff is difficult to burn and, in many cases, incineration does little to reduce either its volume or its chemical potency. Pyrolysis has been proposed for both automobile tires as well as sheet molding compound and, while the feasibility of this approach has been demonstrated, it seems to do little to reduce landfill requirements in the case of SMC, unless the char can be used in other products.

Faced with high tipping costs, many shredder operations are following the example of the nuclear power industry by storing their wastes against the development of a feasible disposal technology [32]. Of course, this merely exchanges one cost (land) for another (landfilling). However, it may prove to be a prudent choice if the necessary technologies are developed before they run out of storage space.

The peculiarities of the scrap market limit the opportunities of scrap dealers to pass along their increases in processing costs to their customers. While increases in supply certainly will depress the price of scrap, a decrease in supply or increase in demand does not guarantee rapid increases in price, if only because there are substitutes available.

Another potential driver could arise with the opening of the Eastern bloc. A viable trade in scrap steel could boost the price of ferrous scrap sufficiently to restore the viability of the automobile shredder industry while awaiting the necessary technological developments. The recent run-up in domestic scrap prices has been attributed to recent developments in export markets for ferrous scrap. Of course, the consequences of these increases in scrap price are increased steel prices, which may prove to be a deterrent to the further expansion of export markets. And, perversely, the Eastern Bloc has most recently been a net exporter of scrap, rather than the reverse.

On the polymer side, the primary drive to recycle will come with increases in the costs of the raw materials. Today's markets for recycled packaging resins clearly show that a price discount is likely to be necessary to support the development of a reprocessed resin market. Unlike the EAF and steel, there currently are no new resin synthesis processes which require scrap resin. On the other hand, the potential for steep increases in the price of petrochemical feedstocks will remain a feature of all polymer processing for the foreseeable future.

Legislative/Regulatory Drivers

While this element was not a major one in the 1970's, even then Clean Air requirements limited the burning of auto hulks, further necessitating the development of an improved separation technology. Today's regulatory environment is already fraught with peril for the polymer industry. Sources suggest that some 800 pieces of legislation relating to polymer use, recycling and disposal were under consideration in 1989 [40], and it is unlikely that the situation has changed much today. Recent Wisconsin regulation banning the landfilling of plastic materials by 1992 are particularly appalling to the auto recycling industry. In addition, the proposed legislation to reauthorize and extend the Solid Waste Disposal Act (HR 3735) has definitely drawn the attention of the Institute of Scrap Recycling Industries, who are challenging many of the bill's provisions that would classify potentially recyclable materials as regulatable waste materials [51].

This concern reflects the experience of automobile shredders in Quebec, Canada. There, automobile shredder fluff has been classified as a hazardous waste, primarily because of the concentration of zinc and lead in the leachant. Because there are no hazardous waste sites in Quebec, shredders have been forced to store their own fluff, and their space is rapidly running out. The current regulation, rather than stimulating the development of better recycling practice, is on the verge of putting shredders out of business instead, forcing the provincial government to reassess and reevaluate their policies [52].

Another event looming on the legislative horizon is the upcoming Congressional consideration of reauthorizing the Resource Conservation and Recovery Act of 1976 (RCRA). Congress has asked the Office of Technology Assessment to consider materials usage trends, how they effect the environment, and what consideration of these effects are taken by product designers. The clear intention is to identify if the government should be involved in promoting further consideration of environmental issues during materials selection.

In some ways, the introduction of a federal agenda is welcome, since the bulk of the legislative and regulatory activity has been at the state level. In the absence of a national environmental policy in these areas, the states have each gone their own way, with the expected inconsistencies and incompatibilities. By the same token, the US automobile companies are unwilling to commit to any recycling strategies in the absence of a clear Federal mandate, given the risks associated with prematurely selecting a strategy that may ultimately be incompatible with regulatory mandates.

On the other hand, the European Community has probably taken the lead in regulating the automotive waste stream, by suggesting that automakers might be responsible for establishing the necessary industrial infrastructure. Of course, regulation of the automobile recycle stream in nothing new in Europe. Both Norway and Sweden have had regulations enforcing automobile recycling for some years [13,15]. On the other hand, it has also been suggested that these regulations would not be necessary if the scrap processors in these countries were free to find export markets for (read, increase the price of) their steel scrap.

Nevertheless, the European experiment with enforced automobile polymeric recycling may have an unexpected side effect. Rather than forcing the automakers to find a use for their polymer components, it may instead force the auto companies into the shredder business, since the current shredder operations are profitable only through the sale of the ferrous and non-ferrous scrap their operations generate.

However, at least in the case of Germany, the current strategies seem to focus upon rationalizing the current recycling infrastructure, rather than supplanting it. This strategy may reflect the fact that there are no particular reasons why automakers should be better at scrap processing than the current processors. Their specialty is in the area of product design, where there are opportunities to "design for disassembly." Here, they can do more for recycling by doing this kind of design instead of taking over the back end of the automobile lifecycle. After all, so long as a business can be made in automobile recycling, there will be companies willing to participate in it. In fact, reliance upon this basic economic fact may be the most potent element of this strategy.

Automobile Recycling 1990's: Summary

So, in the end, the problem faced today is really no different than the one faced in the 1970's. In essence, the question is how can today's automobile scrap processor generate a waste stream sufficiently pure that its value offsets the costs of operating his facility and disposing of what materials he cannot sell. The experience of the 1970's showed that if a hulk were not economical to reprocess, it was discarded in such a way that society in general bore the burden for its disposal. It is unreasonable to expect that today's situation has changed in the least. Successful junk car recycling occurs only through the development of the technologies to identify, separate, and process the elements of the scrap car waste stream, and the existence of a free market within which these elements can be profitably sold.

Today's problem is a consequence of the lack of the technologies to accomplish the separation of this waste stream. While in the 1970's the resolution of this identical problem was the development of a technology which eliminated the need for hand stripping of the automobile hulk, the technologies being developed today seem to focus upon a return to at least some form of hand stripping. Certainly, the introduction of labeling standards seem directed toward this mechanism. It will be interesting to see whether the advent of advanced materials will mark a return to an old fashioned way of doing business for the scrap processor.

And it is becoming increasingly apparent that these technologies will be required, because US automakers are seemingly unwilling to give recyclability primary importance when designing cars and specifying advanced materials. The scale of both automotive and polymer supplier research and development in the area of fiber reinforced composites suggests that the automakers will continue to explore and employ a wide range of polymers and fiber reinforced composites, in spite of their inherent recycling difficulty. Pressures upon the automakers to reduce vehicle weight to achieve ever better fuel economy are likely to continue current material trends in the industry. For example, market predictions put annual growth in the rate of automotive polymeric usage between 1989 and 1994 of 8.7%/year for engineering plastics, 9.8%/year for thermoplastics elastomers, and 14.6%/year for reaction injection molded resins. Of these, usage of the first two is relatively small today, but reaction injection molded materials are being consumed today at a volume of 162 million pounds in the light transportation sector [53]. And, of course, reaction injection molded materials are thermoset resins.

In fact, a recent article in *American Metal Market* states a typical automaker's expectations and attitudes nicely:

> **Singapore -** Autos through 1995 are being designed with more plastics but with no thought applied to recycling the material, a Ford Motor Co. executive told the shredder committee of an international scrap association here.
>
> Decisions on what materials to use in cars will be largely dictated in the United States and Japan by performance requirements. Recyclability will only be a factor when the choice is among materials that perform equally well, Santokh S. Labana, manager of Ford's Polymer Science Department, said....
>
> As a result of carmakers paring down weight to gain greater fuel efficiency, auto shredding operations will see the magnetic separation (ferrous scrap) per vehicle dropping in 1995 to 1,874 pounds from 2,315 this year and 2,822 pounds in 1980,... Conversely, the volume of shredder waste will rise this year alone to almost 300 pounds from 220 pounds [54]

Given the economic and product development pressures the automakers face, it is probably unrealistic to expect them to act any differently. While they certainly recognize the problem, they also recognize that the solution to the problem is not purely the province of the automobile OEMs. A firm commitment throughout the automobile industry, by both suppliers and consumers, will be required to face and resolve these problems. And, in the absence of this commitment, the automobile shredder's problems are going to get a lot worse before they get any better.

Appendix **-** Average Automobile Materials Content
Ward's Automotive Yearbook
All values pounds per car

Year	**1976**	**1977**	**1978**	**1979**	**1980**	**1981**	**1982**
Plastics	162.5	168	180	185	195	198	200
Aluminum	85.5	97	112.5	119	130	130	134
Copper	32	35.5	29	28.5	28	27.5	28
Zinc	44	38	31	25	20	17	15.5
Lead	25	25	24	23	22.5	23.5	
Other Ferrous	71.5						
Iron	562	540	512	498	484	470	461
Carbon Steel	2075	1995	1915	1846	1737	1602	1469
HS Steel	120	125	133	150	175	190	203
Stainless Steel	28	26	26	27	27.5	26.5	27
Glass	87.5	86	86.5	85	83.5	83	84
Rubber	153	150	146.5	137.5	131	133	135
Fluid	190	200	198	189	178	175.5	179
Other	196	133.5	175	162	151	153	155
Total	3760.5	3665.5	3569.5	3475	3363	3228	3114

Year	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**
Plastics	200	204	211.5	216	221.5	223	224.5
Aluminum	136	136.5	138	139.5	146	149	155.5
Copper	39	43.5	44	46	46	49	49.5
Zinc	17.5	17.5	18	18	18	19.5	20
Lead							
Other Ferrous	71.5	54	73.5	55	75	45	68.5
Iron	474	481	468	465.5	460	457	459
Carbon Steel	1511	1526	1481	1470	1450	1440	1416
HS Steel	207	210	217.5	223.5	228	232	234
Stainless Steel	28	28.5	29	30.5	32	31	31
Glass	85	85.5	85	85.5	86	85	85
Rubber	137.5	138	136	134.5	135.5	134	134.5
Fluid	183	189	184	181	183	178	179.5
Other	103	118.5	101.5	105	97	124.5	83
Total	3192	3232	3187	3170.5	3178	3167	3140

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    No 2. Heavy Melting Steel - Wrought iron and steel scrap, black and galvanized, 1/8 inch, and over, in thickness, charging box size to include material not suitable as No. 1 heavy melting steel. Prepared in a manner to insure compact charging.

    No. 2 Heavy Melting Steel - Wrought iron and steel scrap, black and galvanized, maximum size 36 x 18 inches. May include all automobile scrap properly prepared. (The identical designations given for these two classifications in accordance with established industry practices in specifying the materials desired.)

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