A Model for Material Flows and Economic Exchanges Within the U.S. Automotive Life Cycle Chain

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Abstract

A simulation model for material flows and economic exchanges within the U.S. automotive material life cycle chain is presented. The model is employed to examine the effect of future changes in vehicle material composition on the automotive recycling infrastructure. The model results indicate that as vehicle material composition changes, higher dismantling/recovery rates are needed to ensure economic viability of the recycling infrastructure. Furthermore, even in the case of significantly higher rates of dismantling and plastics recovery, the amount of shredder residue per vehicle will continue to rise.

Keywords: End-of-Life Vehicle (ELV), Automotive Recycling, Simulation, Material Flow, Economics

Introduction

Automobiles are perhaps the most highly recycled product in the world, with about 95% of end-of-life vehicles entering the recycling stream in the United States (about 75% of the mass of each vehicle, mostly ferrous content, is recovered) (Cobas-Flores et al. 1998). Approximately 12 million tons of steel and 800,000 tons of nonferrous metals are reclaimed each year through vehicle recycling in the United States alone (ISRI 2001). Motivated by environmental concerns, the automotive industry is planning future product changes (e.g., lighter vehicles and hybrid engines) and is also paying increased attention to the management of the vehicle life cycle (e.g., increased levels of dismantling and vehicle leasing). The effect of these changes on the future economic sustainability of the vehicle recycling infrastructure is, at present, unknown.

The 25% of the vehicle mass that is not recovered usually ends up in a landfill in the form of automotive shredder residue (ASR). Every year in the United States about 3 million tons of ASR is landfilled (Jody et al. 1994). To reduce the amount of ASR, recently enacted regulations in Japan and Europe call for a 95% material recovery rate by 2015. Because most vehicle manufacturers have a global presence, regulatory changes elsewhere have renewed the interest in the topic of automobile recycling in the United States (Field et al. 1994). It could be argued that increasing attention to automobile end-of-life and take-back initiatives will lead to a number of structural changes in the automobile recycling infrastructure. Failure to consider the economic sustainability of the infrastructure could result in a proliferation of junk vehicles similar to that experienced in the United States in the 1970s. This proliferation resulted from a fundamental change in steelmaking technology that could accept only small quantities of automotive scrap (Graedel and Allenby 1998).

This paper presents a model for the behavior of the automobile recycling infrastructure and uses historical data to validate the model. The model has utility in characterizing the effect of potential industry changes on the economic and environmental sustainability of the infrastructure.

Automobile Recycling in the United States

Figure 1 shows the primary material flow exchanges in the automobile material life cycle. A long
chain of suppliers precedes the final manufacturing and assembly of the automobiles by the original equipment manufacturers (OEMs). The end user may dispose of the vehicle with a body shop, a dismantler, or a shredder. The principal participants in the U.S. automobile recycling infrastructure include dismantlers, shredders, and nonferrous separators. The solid waste (that is, the ASR) is generally landfilled, although progress in recycling, reuse, and energy recovery of/from ASR continues to be made.

Most end-of-life vehicles (ELVs) end up with dismantlers (traditionally known as “junk yards”), who pay between $50 and $2,000 per vehicle depending on the age of the scrapped vehicle and the perceived value of the parts/materials in the vehicle. Most dismantlers (~85%) are small, family-owned businesses employing 10 or fewer people (ARA 2001). The total number of such dismantlers in the United States is estimated to be about 6,000. A dismantler removes parts like the engine, transmission, radiator, catalytic converter, fuel, fuel tanks, fluids, tires, batteries, and air bags from the car before selling it as a hulk (that is, the remains of the ELV after the dismantler is finished with it) to a shredder. The amount of plastic recovered by dismantlers is estimated to be very small, as the majority of vehicles that are currently being retired were designed/manufactured more than 12 to 15 years ago, when the concepts of design for recycling and design for disassembly were in their infancy. The dismantler bears the cost of transportation of the hulk—about $15 per ton for an average distance of 160 km (APC 1994).

A shredder buys the hulk from a dismantler purely for its material content. Typical hulk prices vary between $50 and $100 (Staudinger, Keoleian, and Flynn 2001). It is estimated that there are between 180 and 200 shredders in the United States (Das, Curlee, and Schexnayder 1997). Most shredders can handle 400–500 hulks per day.

After shredding, the shredder sells the ferrous scrap to ferrous recyclers, at a price of about $80 to $120 per ton. The nonferrous metals are sold to a nonferrous separator (about 40 in the United States), and the light shredder residue is generally landfilled. The nonferrous scrap can be purchased for $700–$800 per ton, whereas the cost of landfill depends on the density of the shredder residue, the landfill price per unit volume, and location. The light fraction of the shredder residue needs to be landfilled in an EPA subtitle D landfill where the tipping fees range from $15 to $26 per cubic meter. For an estimated ASR density of about 300–350 kg/m$^3$, the disposal rate works out to be in the range of $50–$75 per ton. The cost of disposal of hazardous materials is higher, in the range of $70–$120 per ton.

A typical nonferrous separation facility has a capacity of 25 ton/hr and operating costs in the range of $80–100 per ton (Das et al. 1999). The main source of revenue for the nonferrous operators is aluminum scrap, whereas purchasing feedstock material constitutes a large fraction of the costs. Because the shredder already separates the heavy fraction of the ASR, the amount of material that needs to be landfilled by the nonferrous operator is dependent on the efficiency of the shredding operation.

The amount of solid waste produced at vehicle end-of-life is estimated to be about 325 kg, of which about 300 kg is ASR. Because ASR is landfilled in most places as municipal/industrial waste, it represents an economic loss to the shredders and nonferrous separators. Based on the above discussion, the material recovery rate varies across the recycling chain. Estimates of recovery rates at each recycling stage are shown in Table 1.

A background on automobile recycling in the United States has been presented that will serve as a basis for developing the simulation model for evaluating the material flows in the automobile material life cycle to be presented in the next section.
MFEE (Material Flows and Economic Exchanges) Model

A typical material transformation activity can be conceptualized as shown in Figure 2. The inputs and outputs of a particular transformation activity or model sector are affected by the variables and parameters used to characterize them, which in turn depend on technological and regulatory constraints.

A material flows and economic exchanges (MFEE) model has been developed using VENSIM by Ventana Systems to describe the material flows in the automotive life cycle industry chain in terms of new cars and cars already present on the road; the vehicles are described in terms of their average mass and five types of material classes, that is, ferrous, aluminum, other nonferrous materials, plastics, and miscellaneous. The simulation models the automobile material life cycle in terms of stocks and flows of the automobiles. The stocks represent the number of automobiles at a particular stage in their life. The stocks (or levels) can vary only through the flows (or rates), which may depend on the current value of the stocks themselves and/or other variables. The materials and the associated cash flows are calculated concurrently with the flows of the automobiles. The simulation model is capable of reading a set of time-varying model inputs and parameter values. The simulation also considers important system performance variables (such as the profitability of dismantlers and the ASR generated per vehicle).

Mathematical Basis for Simulation

VENSIM is a general-purpose simulation package that utilizes a stock-flow approach to describe system dynamics. For an activity such as that depicted in Figure 2, rates are established for each input (e.g., $q_1$ and $q_2$). These rates of change, as noted above, may be dependent on the settings for other variables and parameters. $q_1$, for example, may be the vehicle sales per month. The rate of change in each output associated with an activity is then described in terms of the inputs, as follows:

$$\frac{dO}{dt} = q_1(t) + q_2(t) \quad (1)$$

VENSIM provides several methods to integrate equations of this form to obtain the output as a function of time.

MFEE Model Components

As vehicles are produced, they enter the usage stage of the life cycle and undergo aging (aging chain). At the end of the usage stage, the vehicles are recycled (recycling chain). Brief descriptions of these two key portions of the MFEE model are provided below.

Aging Chain

For convenience, the vehicle aging chain is broken down into four stages. The total number of vehicles on the road is the sum of all the stocks of cars in all age groups. At each stage, a certain fraction of the automobiles retire, and those remaining enter into the next age group. The retirement fractions are based on values extracted from the literature and are reported by Bandivadekar (2002). The retiring vehicles are further classified as “new ELVs” or “old ELVs.” All the vehicles retiring at eight years of age or younger are termed new ELVs, with the others grouped as old ELVs. A certain fraction, approximately 5%, of deregistered vehicles is assumed to be abandoned. This abandonment is usually a result of accident or lack of a nearby dismantling facility. Abandoned vehicles are modeled as “old ELVs.”

### Table 1
Rates of Automobile Recovery/Disposal by % Weight (Das et al. 1999)

<table>
<thead>
<tr>
<th>Material</th>
<th>Dismantler</th>
<th>Shredder</th>
<th>Nonferrous Separator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>35</td>
<td>64</td>
<td>1</td>
</tr>
<tr>
<td>Iron</td>
<td>90</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>Aluminum</td>
<td>15</td>
<td>20</td>
<td>65</td>
</tr>
<tr>
<td>Plastics</td>
<td>0</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>Copper</td>
<td>20</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>Zinc</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Other</td>
<td>50</td>
<td>50</td>
<td>0</td>
</tr>
</tbody>
</table>

### Figure 2
Input/Output Representation of Material Transformation Activity

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Recycling Chain

The post-retirement processing of the new and old ELVs is represented by separate recycling chains. Each recycling chain consists of three stages: dismantling, shredding, and nonferrous separation. While the 6,000 or so dismantlers have the capacity to handle 80% of the ELVs, the remainder are shredded directly (Duranceau and Lindell 1999). The rate at which the ELVs or hulks are processed controls the stock of ELVs and hulks. The time taken to process in turn depends on the inventory control policies of the recyclers. For example, it is estimated that an old ELV may remain with a dismantler for as long as two to five years (Staudinger, Keoleian, and Flynn 2001).

MFEE Model Calculations

The MFEE model may be used to calculate a variety of critical measures of performance, some of which are detailed below.

Material Flows

The model tracks the vehicle weight as well as the flows of five basic materials, that is, ferrous, aluminum, other nonferrous, plastics, and miscellaneous. The fraction of materials used in new cars and the average weight of new cars are inputs, and the actual weights of the materials in the cars are calculated from the number of automobiles and the average weight fraction of each material at every stage.

The critical parameters of interest are the fractions recovered by dismantlers, shredders, and nonferrous separators from ELVs. As discussed previously, the dismantler can remove material for its part value or for its scrap value. It is assumed that shredders and nonferrous recyclers are able to realize recovery efficiencies as shown in Table 2. The fraction not recovered (that is, the ASR) is assumed to be landfilled.

Dismantler Profit Calculation

Figure 3 displays the input, output, parameter, and constraint variables faced by a dismantler. Similar illustrations may also be constructed for a shredder or a nonferrous separator.

The dismantling operations are constrained by the costs and mandatory part removal requirements. The dismantler’s monthly profit is calculated as the difference between revenue (from part, material, and hulk sales) and costs (purchase of ELVs, labor, transportation, and disposal). The revenue depends on the number of parts sold and part values, the amount of material scrap and scrap prices, and the number of hulks sold. The costs depend on the labor rate, time required for dismantling (which is again dependent on the fraction of materials the dismantler intends to recover), number of ELVs purchased, purchase price paid for the ELVs, amount of material disposed after removal, and cost of disposal. The revenue gained from the parts is estimated as half the cost of new parts (Das et al. 1999).

Shredder Profit Calculation

A shredder derives revenue mainly from the ferrous scrap that is recovered, however, another source of revenue is commingled nonferrous scrap. Major costs include operational costs, purchase of hulks and ELVs, transportation costs, and costs of disposal. The capital cost of a shredder with a capacity of 70 ton/hr is about $3–$4 million. Over a period of 12–15 years of operation, this translates to less than $3 per hulk processed. Because hazardous and nonhazardous materials to be disposed are not considered separately in the model, a higher cost of disposal is assumed at $66/ton as opposed to commonly reported costs of $30–40/ton.
Nonferrous Operator Profit Calculation

Nonferrous separation is the last step in the automobile recycling activity. Approximately 40 such operators are presently in operation in the United States. The feedstock costs represent most of the costs of a nonferrous separation operation. The nonferrous metals separated (including aluminum) are the main source of revenue, and profits typically exceed costs by 14% (Das et al. 1999).

MFEE Model Limitations

The MFEE model characterizes various stages in the automobile material life cycle. The model can be utilized to evaluate the flows of five major classes of automobile materials over time. The economic effects of any changes in material composition and vehicle mass on the recycling infrastructure can be evaluated. However, the model has several limitations, as described below:

- An average automobile consists of more than 20,000 different parts and more than 100 different types of materials (or their variants). The model is highly aggregated and a number of approximations about material and parts prices are necessary.
- The model assumes a certain fraction of material recovered at the dismantling stage. Although the fraction of material recovered is accurately expressed from a total material standpoint, the dismantler actually recovers a particular part rather than a material fraction.

The model also does not account for the effect of volatility of scrap prices and its effect on the inventory levels of the dismantlers. In addition, the U.S. OEMs play no direct part in automotive recycling, however, the OEM material selection and design decisions ultimately control vehicle recyclability. The model does not attempt to capture the behavior of OEMs in making these decisions, that is, the material composition, weight, and the vehicle technology are assumed as exogenous variables. The authors continue to perform research to enhance the MFEE model to address some of these limitations.

MFEE Model Validation

The previous section described a simulation model that described the material flows and economic activity associated with the U.S. automobile recycling system. Before using the model to examine the impact of various future scenarios, the model must first be validated with historical data. The historical data (e.g., car sales and average material composition) were extracted from automotive industry records (Ward’s 2000). The validation simulation focused on the time period for which historical data were available (1976–2000). Table 3 shows the initial conditions for the simulation in terms of the number of cars in each age group and the average material composition.

As reported by Bandivadekar (2002), for the last several decades dismantler and shredder profits have been $15–$20 and $5–$10 per vehicle, respectively. Figure 4 shows the model-predicted dismantler and shredder profits for this time period. The model predictions fall within the uncertainty band associated with the historical dismantler and shredder profits. The profit of a nonferrous separator is highly dependent on the feedstock price and the scrap for nonferrous material recycled; for the historical time period, the actual and model-predicted profit were both approximately $30 per ton of scrap processed. In summary, the simulation provided accurate predictions of the characteristics extracted from the historical data.
record (e.g., profitability of stakeholders in recycling infrastructure, number of ELVs, number of vehicles in the road, and ASR quantity).

**MFEE Model-Predicted Future Behavior**

The MFEE model has been validated with historical data; it is capable of describing the material and economic dynamics of the automotive recycling infrastructure. Attention may now be shifted to using the MFEE model to predict what will happen to the recycling infrastructure in the future. Of course, the future behavior of the infrastructure is highly dependent on future automobile designs, and there is considerable uncertainty in what these designs will look like. To account for this uncertainty, three scenarios were evaluated using the model with varying vehicle material composition and weight over the next 30 years (that is, simulations from 2000 to 2030).

- **Scenario 1 (Nominal Scenario):** In this scenario, it was assumed that the current trend of replacing ferrous material with plastics and aluminum will continue. The average vehicle mass was assumed to decrease linearly from its current value of 1500 kg to 1417 kg by 2030.
- **Scenario 2 (Aluminum Intensive Vehicle):** In this scenario, it was assumed that ferrous materials are primarily replaced by aluminum. The overall vehicle weight dropped to 1189 kg.
- **Scenario 3 (Plastics/Composites Intensive Vehicle):** It was assumed that ferrous materials are primarily replaced by plastics/composites. The overall weight drops to 1189 kg.

Of course, in addition to the uncertainty in future vehicle composition, additional future uncertainties are also present (e.g., dismantling rates for various materials, shredding efficiency, and vehicle sales). These uncertainties have been captured through the nine cases depicted in Table 4 (Cases A-I); the table lists values for the indicated parameters. The MFEE model was run for each scenario/case combination (a total of 27 runs). Case-to-case differences for each scenario largely reflect uncertainties within the recycling infrastructure.

**Model Results**

Based on the 27 simulations that were performed (three scenarios x nine cases), several observations can be made. The dismantling operations were the most sensitive (compared to shredding or nonferrous separation) to the scenario type. Aggressive recovery of aluminum and ferrous parts by dismantlers appears to be required to maintain profitability. Shredders and nonferrous separators will benefit from additional amounts of aluminum in vehicle hulks. The average weight of the hulks was not found to decrease appreciably over the duration of the simulation, as ferrous will continue to be the main constituent of the hulk material. Thus the ferrous scrap prices will continue to affect shredder profit.

Several graphs were prepared to illustrate the MFEE model predictions. Figure 5 shows the predicted dismantler profit for the next 30 years for the nominal scenario. For each year, a range of profits is illustrated, corresponding to the range in profits associated with the nine cases.

Figure 6 displays the predicted dismantler profit for the case of the aluminum intensive vehicle (AIV).
The uncertainty band in the figure is again associated with the range of profits predicted for the nine cases. As noted above, the dismantler profitability associated with the AIV scenario is less than for the nominal scenario.

Figure 7 displays the predicted shredder profit for the case of the composite intensive vehicle (CIV). This scenario represents the worst possible scenario for the shredder (compared with nominal and AIV scenarios). The margin of profitability is small, but all cases do predict positive profit.

Figures 8 and 9 illustrate the predicted levels of ASR for the nominal and CIV scenarios, respectively. The predictions show that even with a moderate increase in the amount of plastics in the vehicle in the coming years, the amount of ASR will continue to increase. The ASR produced per vehicle can be expected to increase from its current level of 17% to more than 20% of the vehicle weight in the next 30 years. This results in an absolute increase in the amount of ASR, assuming that vehicle sales figures remain fairly stable.

Summary and Conclusions

Recycling is an absolutely critical activity within the U.S. automotive industry life cycle chain. In the absence of an economically stable recycling infrastructure, ELVs will begin to accumulate, representing a negative environmental impact and placing additional burden on automotive manufacturing in terms of primary material usage. This paper has described the development of a simulation model for the material flows and economic exchanges within the automotive recycling infrastructure. Model predictions show reasonable agreement with historical data.

The following conclusions can be drawn from this research:
• Even in the case of significantly higher rates of dismantling and plastics recovery, the amount of ASR per vehicle will continue to rise. This means that the Japanese/European recycling target of 95% by 2015 seems unattainable without dramatic/fundamental changes.

• The capital costs of the stakeholders within the recycling infrastructure are not significant when compared to material acquisition costs. The disposal costs also do not appear to be a significant factor affecting the economics of shredding at present.

• The recycling infrastructure will retain enough economic incentive to ensure its sustainability in the event of changing vehicle material content. However, to maintain their profitability, dismantlers may have to resort to much higher levels of dismantling than are currently employed.

While not considered in this study, it may be that, as in Europe/Japan, government intervention (via regulation or incentive) will be needed to achieve 95% material recovery rates in the United States.

References

Authors’ Biographies
Anup Bandivadekar holds a bachelor of engineering degree from the University of Mumbai and an MS degree in mechanical engineering–mechanics from Michigan Technological University. He is presently a graduate student in engineering systems at the Massachusetts Institute of Technology. His research interests are focused on developing frameworks and methods to achieve a sustainable transportation system.

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Kenneth L. Gunter received his PhD from Michigan Technological University in 2004. His research addresses the environmental issues related to mechanical and manufacturing engineering, and he has focused on product end-of-life issues, particularly value management in demanufacturing systems. His research has also examined cutting fluid mist formation and air quality issues in manufacturing processes. He has published nearly 20 papers in various journals and conference proceedings and is the coauthor of the chapter “Environmental Attributes of Manufacturing Processes” in the Handbook of Environmentally Conscious Manufacturing.

John W. Sutherland is the Hennes Chair Professor in the Dept. of Mechanical Engineering–Engineering Mechanics and director of the Sustainable Futures Institute at Michigan Technological University. He received his BS, MS, and PhD degrees from the University of Illinois at Urbana-Champaign. His research and teaching interests include environmentally responsible design and manufacturing, quality engineering, and manufacturing systems. He has published nearly 200 papers in various journals and conference proceedings. He has served as an investigator on numerous grants and has mentored more than 50 students to the completion of their graduate degrees. Dr. Sutherland was the recipient of the Outstanding Young Manufacturing Engineer Award from the Society of Manufacturing Engineers in 1992, Michigan Tech Distinguished Teaching Award in 1992, Presidential Early Career Award for Scientists and Engineers in 1996, SAE Teetor Award in 1999, and Michigan Tech Research Award in 2000. He is a member of SME, CIRP, ASME, IIE, ASQ, SAE, Tau Beta Pi, Alpha Pi Mu, Phi Kappa Phi, Sigma Xi, and Pi Tau Sigma.