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IMPACT OF HYBRID AND ELECTRIC VEHICLES ON AUTOMOBILE RECYCLING INFRASTRUCTURE

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ABSTRACT

The recycling infrastructure for end-of-use vehicles in the United States is driven by profitability due to the absence of regulations. Typically, the recycling consists of removing reusable components for resale and shredding and separating remaining material for material recovery. Profitability depends on the quantity and type of components and material recovered. Because the material composition of hybrid and electric vehicles differs from conventional vehicles, their increased presence is expected to affect profitability. Understanding the impact of these vehicles on recycling profitability is the focus of this paper. It uses a system dynamics model to analyze that impact on the profitability of dismantler and shredder operations over the coming years.

1 INTRODUCTION

Sustainable manufacturing implies that end-of-life products be recovered and recycled, thereby reducing the demand on quickly depleting natural resources. The U.S. automotive industry recycles about 95% of the products (Bandivadekar et al. 2004). This high rate of recycling occurs primarily because of the profit margins of the associated players, including dismantlers and shredders. Those margins depend on the composition of the conventional end-of-life vehicles (ELVs) – specifically on the usable components and their material makeup. Dismantlers remove salvageable components and hazardous materials from an ELV and crush them into hulks for transportation to the shredder. The shredders use huge hammers to grind the hulks to allow separation of the materials. The materials are separated into those that can be sold as bulk and those that have to be sent to landfill - known as automotive shredder residue (ASR). The shredder has to pay a fee for the ASR sent to landfill. Dismantlers' profits depend on the price they get for salvaged components. Shredders' profits depend on the price they get for recovered materials that can be sold as bulk.

The profitability of automotive recycling depends strongly on the composition of vehicles. That composition is changing because the push for alternative energy sources and higher fuel efficiencies has increased the demand for hybrid and electric vehicles. That push started with the availability of hybrid vehicles that have both an internal combustion engines (ICE) and electric motors. Hybrid vehicles became available at the turn of the century and their volumes have increased over the years - though they still command only a small percentage of the automotive market. The end of 2010 saw the first mass-market availability in the U.S. in the 21st century of purely electric vehicles that have no ICE. These vehicles use more plastics and composite materials than conventional vehicles, which use primarily steel. They also have a large fraction of their weight devoted to rechargeable batteries that are handled separately. Since the composition of both hybrid and electric vehicles differs quite dramatically from conventional vehicles, there is some concern about the impact on the profitability of the recycling infrastructure of the automotive industry in the long term.

This paper analyzes that impact. Of particular concern is that the push to improve the environment by using hybrid and electric vehicles may actually (1) reduce the overall profitability of recycling and (2) end up hurting the environment in the long term! Understanding the potential impact at this early stage will allow new policies and cost structures to be developed that keep the automotive recycling infrastructure profitable and thus operational. The scope of this paper does not include an analysis of such policies and structures. A model is proposed instead that might prove useful for such explorations in future.

The paper is organized as follows. Section 2 reviews the recent recycling literature with special emphasis on its profitability. Section 3 provides the specific objectives and approach used for this study. Section 4 presents a sustainable manufacturing framework for system dynamics modeling and a description of the model developed for this study. Section 5 describes the inputs to that model and Section 6 discusses the results of the analysis of scenarios with hybrid and electric vehicles sales projections and its implications. Section 7 presents our conclusions.

2 LITERATURE REVIEW

This study uses an approach based on system dynamics. Such an approach has been used for both forward and reverse supply chains. In his ground breaking book on system dynamics, Sterman (2000) includes multiple applications to supply chains include two on reverse supply chains.

It was Chen (1994) that constructed and demonstrated an early system dynamics model for automobile recycling. Zamudio-Ramirez (1996) addresses the part recovery and material recycling in the US auto industry. Taylor (1999) analyzes the market structure of paper recycling and the associated impact on prices and flows. Boon et al. (2001) used goal programming techniques to study the flow of aluminum intensive vehicles through the automotive recycling infrastructure. They concluded that the infrastructure, which was designed for steel intensive unibody vehicles, would remain with the shift to aluminum intensive vehicles. Boon et al. (2003) did a similar study on the impact of hybrid and electric (or clean) vehicles. They acknowledged the limitation of the linear assumptions of goal programming, but pointed to informative first order results. Those results implied that the clean vehicles might be profitable to process if (1) there were a market for the parts and (2) there were sufficient quantities of non-ferrous materials (aluminum, copper, zinc). The paper provides useful data on vehicle composition, some of which we have used in this paper. Our study uses system dynamics modeling and has the benefit of production and sales data current as of 2011, almost a decade later than the earlier study.

Bandivadekar et al. (2004) studied the U.S. automotive life-cycle chain using system dynamics and analyzed the impact of the changing composition of the vehicles. They concluded that the fraction of vehicles being recycled needed to increase to maintain the viability of the recycling infrastructure. While they referred to an increasing use of the hybrid vehicles they did not address the issue of battery removal directly that is explicitly addressed in our study.

Edwards et al. (2006) discussed the economics of recycling in the United Kingdom in view of the ELV directive of the European Union (EU). The directive calls for 95% recovery and 85% recycling by weight of vehicles by 2015 and includes provisions for the removal of fluids and batteries. They reported that the added removal costs had been absorbed by the high value of scrap steel. They suggested that, going forward, the market for recycled polymers should be exploited to support the dismantlers (identified as authorized treatment facilities). Ferrão et al. (2006) also focused on the EU ELV directives and model strategies to meet the EU directive targets. They concluded that ASR mechanical separation and recycling technologies were promising ways to help meet the targets.

Kumar and Yamaoka (2006) used system dynamics simulation to study and compare the closed loop supply chains of U.S. and Japanese automotive industries. They reported that 55 % of used cars are exported from Japan and suggested that the Japanese government support automotive recycling in the import countries. For U.S., they reported that extended car life cycles actually reduce both the demand for new cars and the recycling of old cars. They recommend that the U.S. government provide incentives for new or environmental friendly cars and enact laws for ELV and periodical environmental inspection.

Kumar and Sutherland (2008) reviewed the research on sustainability of automotive recycling infrastructures. Their conclusions included the need (1) for improved models to study the interactions of involved stakeholders and (2) to study several questions including energy issues, life cycle CO2 emissions, and the impact of light-weight materials.

The literature review indicates the importance attached by several researchers to the issue of economic viability of the automotive recycling infrastructure, especially in Europe. Increased attention in the research domain will help generate the data that may then be used for convincing policy makers to explore new policies to sustain the automotive recycling infrastructure.

3 STUDY OBJECTIVES AND APPROACH

This study involves two major activities. The first is to evaluate the impact of the increasing numbers of hybrid and electric vehicles on the profitability automotive recycling, the dismantler and shredder segments in particular. The second is to develop an initial modeling capability that can be iteratively enhanced to include larger numbers of stakeholders and relevant issues.

Similar to several works described above, our study uses a system dynamics model to perform the evaluation. That evaluation is based on a comparison of a forecasted scenario with a base scenario containing conventional vehicles only. We attempt to improve on those works by (1) using current data on the actual and forecasted sales of conventional, hybrid, and electric vehicles and (2) modeling their individual flows through life-cycle stages rather than as a representative average vehicle. This allows us to model the impact of large battery packs used in the hybrid and electric vehicles more accurately.

The data for this study has been collected from the literature mentioned in the previous section and on-line sources such as government websites (U.S. International Trade Association 2011, U.S. DoT 2011), automotive publications websites (Ward's Automotive Group 2011, WorldOMeters 2011), and sustainable transportation interest organizations (ICCT 2011). Some of the forecast data was generated using extrapolations from available industry forecasts. In building our system dynamics model, we have made several assumptions, which are described in the next section.

4 MODEL DESCRIPTION

This study is based the conceptual framework for modeling of sustainable manufacturing described in (Jain and Kibira 2010). Presently, we describe that conceptual framework; then, we provide details about the system dynamics model, based on that framework, developed for this study.

4.1 Framework for System Dynamics Modeling of Sustainable Manufacturing

The conceptual framework (Figure 1) allows sustainable manufacturing modeling at different levels of granularity – from global to the manufacturing plant floor. It includes four domains: manufacturing, environmental, financial, and social. Each domain can be modeled fairly independently with some information from other domains provided as variables. The arrows in the framework represent indirect flows of materials and information between the domains or more abstract impacts and interactions. For example, the ultimate goal of any manufacturing firm is to remain financially viable. Such viability can be determined over time through modeling of flows in the financial domain. Finances are used to fund manufacturing activities and pay workers. The manufacturer earns revenue from the sale of products. Manufacturing employs people and contributes to the development of communities. The social domain is used to model the community and people aspects including the market for the products and services.

There are no direct flows between the domains since manufacturing is represented as an entity in each of the other domains. The relevant aspects of the manufacturers are represented in the other domains. Manufacturers are represented as corresponding environmental entities in the environmental domain, as corresponding social entities in social domain and as corresponding financial entities in the financial domain.

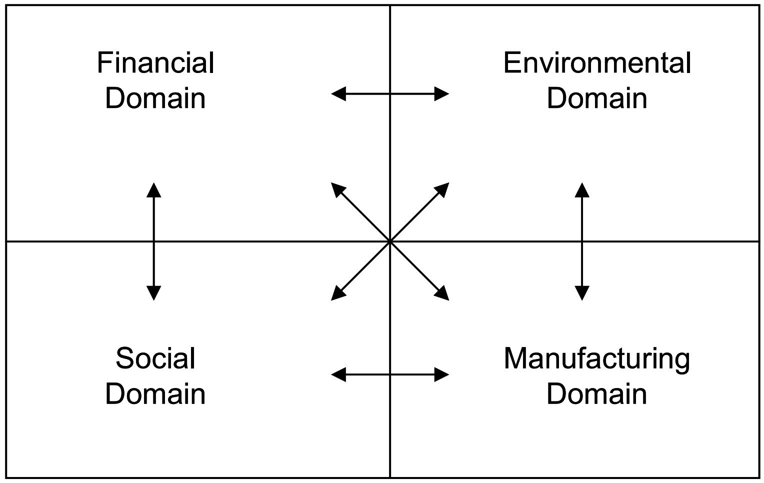

Figure 1: Conceptual framework for system dynamics modeling of sustainable manufacturing

4.2 Input Factors for our Model

The principal inputs into the model are vehicles. There are three types according to the source of power: conventional vehicles, hybrid electric vehicles, and battery electric vehicles. Henceforth, we designate them as “conventionals”, “hybrids”, and “electrics” respectively. The gross material composition of a specific vehicle depends on its designation, and it varies with time. For example, to make them lighter and reduce energy consumption, conventional vehicles contain more composite and aluminum materials than ever before. Hybrids and battery electrics are similar to conventional in material composition, but the batteries are bigger (Boon et al. 2003). In fact, in the newer battery electrics, the battery may weigh as much as an internal combustion engine. Used batteries of hybrids and electrics are rarely recycled. Instead, they may be recovered for reuse in used vehicles. Since hybrids and electrics are projected to increase market share, their presence will impact on the economic viability of the recycling infrastructure.

The model assumes an automobile life expectancy of 4 to 15 years. The dismantler removes components that would contaminate the recycled materials further downstream including the fuel tank, battery, converter, tires, fluids, and airbag. In addition, the dismantler removes subassemblies of commercial value such as instrument panel, transmission system, bumpers, and steering assembly. The dismantler also removes the engine from conventional and hybrids and the battery from hybrids and electrics. Their age and condition, particularly for batteries, determines what happens to them in the downstream processes. For example, some electric batteries can still achieve 80% of their original charge after 10 years of use. These batteries can be sold used for such applications as energy storage from solar panels or wind farms. Lead-acid batteries on the other hand, when sold for recycling, generate about $0.12 per/kg (Boon et al. 2003).

What remains of a vehicle after material recovery is called the hulk. It is crushed, flattened, and transported for sale – between $100 and $150 on average – to the shredder. Some vehicles, about 15%, are sold by owners directly to shredders (Kumar et al. 2008). At the shredder, the hulk is reduced to shreds of metal using a hammer mill.

The dynamic model (Figure 2) combines the activities of shredding and material separation. The materials are classified into ferrous, aluminum, other nonferrous metals, plastics/composites, and miscellaneous. The shredder receives revenue by selling these materials. Ferrous materials sell for $100-$150 per ton. Aluminum generates $750 per ton while other nonferrous metals, about $1200 per ton. The remainder, called automotive shredder residue (ASR), is landfilled at a cost to the shredder. Increasingly, plastics and composite materials are also being recovered as technology is developed. The model assumes that by the year 2020 up to 20% (conservative estimate) of these materials would be recoverable for sale. Figure 2 summarizes the flow of automobiles through use and recycling.

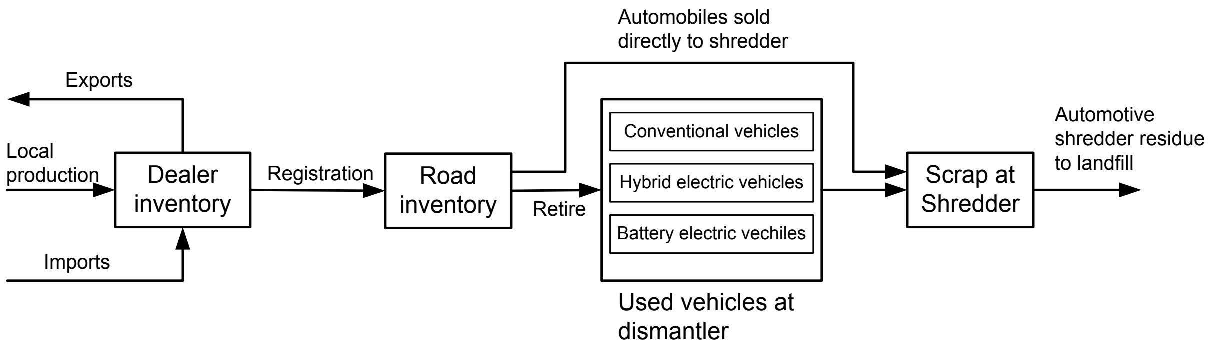

Figure 2: Automobile volume flow in the use and recycling system

Figure 3 shows the material and cash flows for materials and components in the automobile lifecycle including its passage through the recycling infrastructure. As discussed above, the dismantler buys the vehicles, but is paid for the saleable parts removed for reuse - some materials, such as tires, have no commercial value. The shredder pays for the hulks, but is paid by material suppliers for the materials removed. Local material producers purchase scrap from shredders and are paid by local manufacturers for the materials processed.

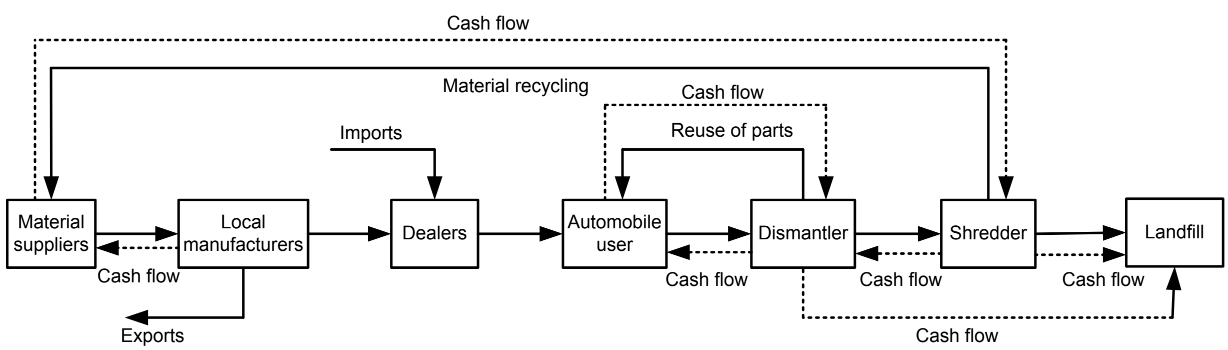

Figure 3: Material and financial flows in the automotive recycling infrastructure

4.3 Input Data

The data to run the model was obtained from different sources including on-line and literature searches. The model uses both historical data (1991-2010) and future projections for (2011-2020). Per the data, hybrids entered the stream in the year 2000 while electric vehicles came in late 2010. Details of some data categories are shown in subsequent tables. Table 1 shows the data categories used.

4.4 System Dynamics Modeling

For this study, we constructed a system dynamics simulation model. That model uses stocks and flows to describe the material and financial flows through the system. A simple example is shown in Figure 4. Mathematically, the inventory (Stock) at any time t is represented by the integral

$$inventory(t) = \int_{t_0}^{t} [production(s) - sales(s)]ds + inventory(t_0)$$

where production(s) represents the value of the inflow at any time *s* between the initial time t_o and the current time *t*.

Table 1: Data used in the model

a) Local production b) Exports c) Imports d) End of life vehicle exports e) Sales data i) Conventional ii) Hybrids iii) Electric f) Recycling rate g) Retire rate h) Percentage vehicles dismantled i) Average vehicle weight – all categories j) Vehicle ferrous composition k) Vehicle aluminum composition l) Vehicle other nonferrous composition	m) Vehicle plastics composition n) Vehicle miscellaneous composition o) Average weight and material composition of i) Airbag ii) Converter iii) Fuel tank iv) Battery – conventional vehicle v) Tires p) Average weight, recovery rate, and average price of i) Engine ii) Transmission iii) Instrument panel iv) Bumper v) Steering wheel	vi) Glass vii) Other recovered components viii) Battery – for hybrid and electric vehicles q) Prices of junked vehicles (conventional, hybrids, and electric) r) Recycling fraction, and material price of i) Ferrous materials ii) Aluminum iii) Other nonferrous metals iv) Plastics v) Miscellaneous s) Investment and operating cost for dismantler and shredder t) Landfill cost u) Hulk and transport cost

Figure 4: Example of stock and flow diagram

For our model, the flows represent the number of vehicles that enter and exit a stage in the life cycle. Stocks represent the number of units or the tonnage of material. The data is externally stored in tables and read into the model during the run. The simulation model reads time varying data inputs and parameters. For example, to describe the tonnage of material from vehicles retiring now, it uses material composition of vehicles manufactured for each of the previous years and the percentage vehicle retiring at each age, 4-15 years. Table 2 has been developed based on data in Kumar and Sutherland (2008) and Boon, Isaacs and Gupta (2003) and shows the material composition of each car type as used in the model.

Table 2: Material composition in kilograms for different vehicle types

Vehicle type & year / *Material*	**Conventional**		**Hybrid**	**Electric (excluding battery)**
	2000	*2020*	*2010*	*2010*
Ferrous	770	432	625	380
Aluminum	93	148	115	100
Other nonferrous metals	46	75	40	50
Plastics/Composites	150	220	145	250
Other materials	191	125	125	125
Total weight	1250	1000	1050	955

Figure 5a shows the stock and flow diagram of the material flow at the dismantler. Figure 5b shows the same for the shredder. These diagrams are for conventional vehicles; similar diagrams have been developed for hybrids and electrics. Additional diagrams are used to express material balance and the calculation of profits but are not included here due to page length restrictions. As shown in the stock and flow diagram, retiring vehicles go through the dismantling and produce the shredder stock. From the shredder, material is either sold or landfilled.

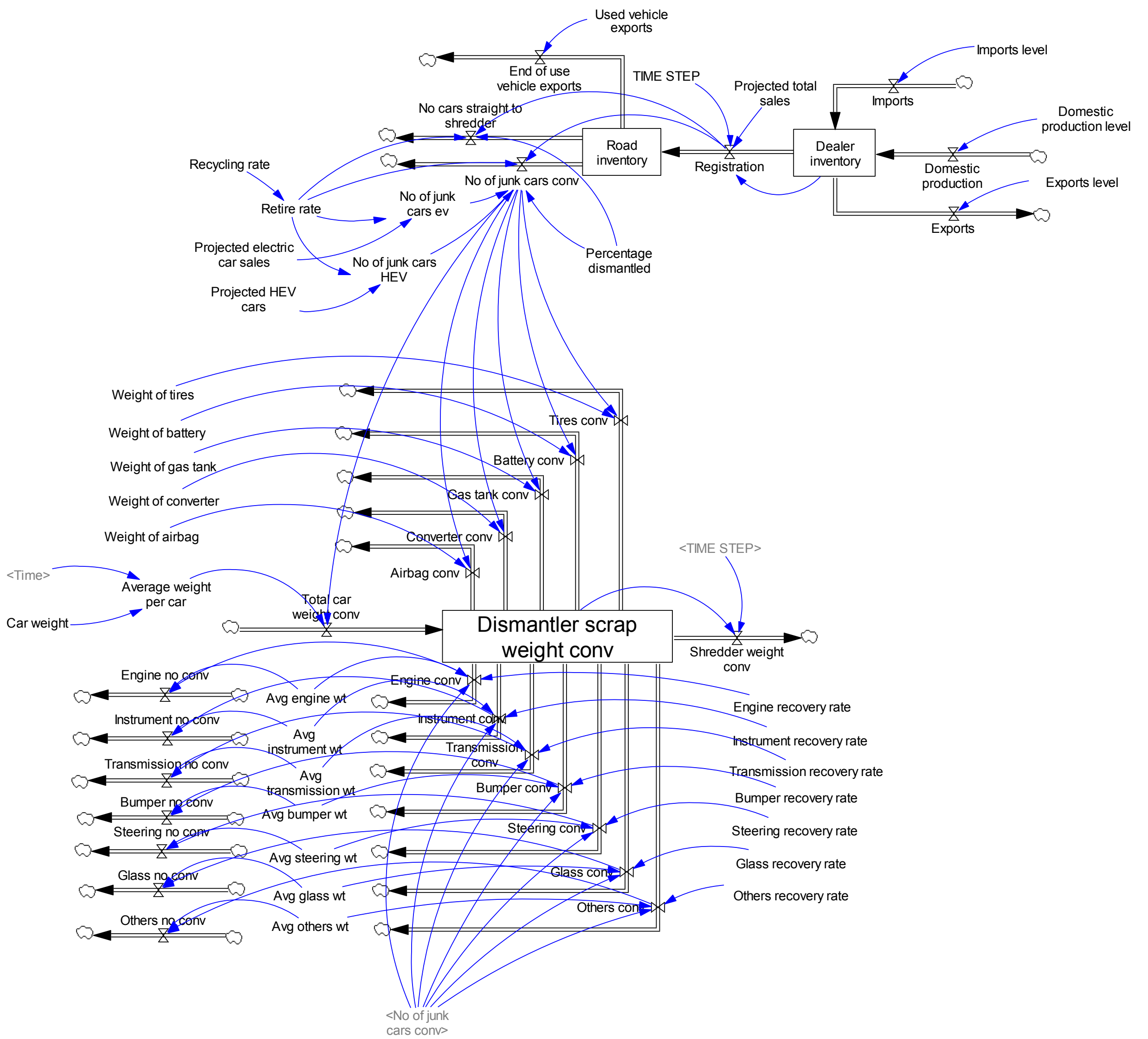

Figure 5a: Stock and flow representation of the dismantler

Table 3 shows the details of the materials removed by the dismantler. Figure 6 shows the high-level model used in the calculation of the dismantling profits. The dismantling processes must include removal of mandatory parts and components. The profits are calculated as a difference between the revenues and expenditure. The costs must also include investment costs since we assume that the dismantling business premises and other assets are acquired as a loan for which regular repayments must be made to service it.

Similar diagrams can constructed for the shredder profits. Table 4 shows the shredder recovery fraction of material and prices.

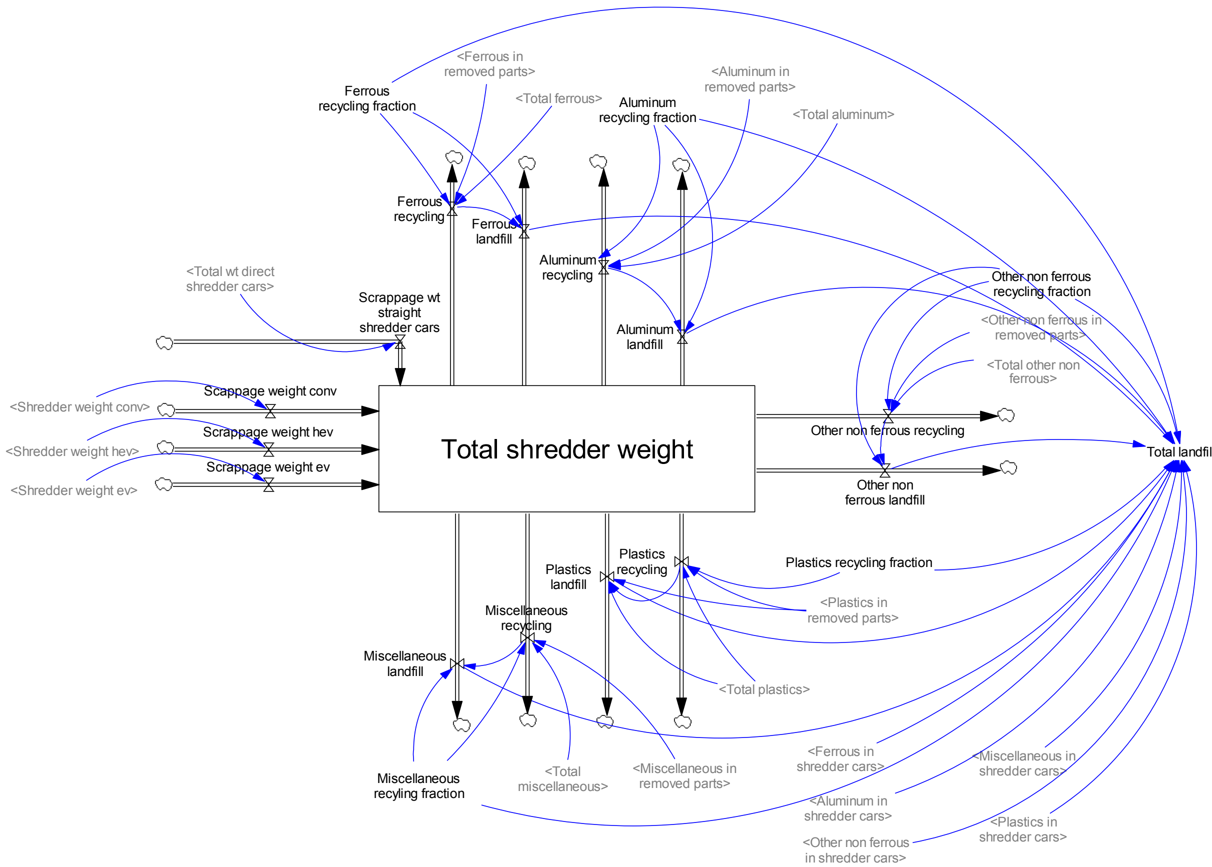

Figure 5b: Stock and flow representation of the shredder

Table 3: Materials recovery, recycling fraction, and prices

Item	Conventional	Hybrid	Electric	Recovery fraction	Price sold ($)
Engine	Y	Y	none	0.1	500
Instrument panel	Y	Y	Y	0.1	80
Transmission	Y	Y	Y	0.35	250
Bumper	Y	Y	Y	0.45	100
Steering	Y	Y	Y	0.35	100
Glass	Y	Y	Y	0.3	75
Battery	N	Y	Y	0.75	70 - 1000
Hulk	Y	Y	Y	1	100
Others	Y	Y	Y	0.1	50

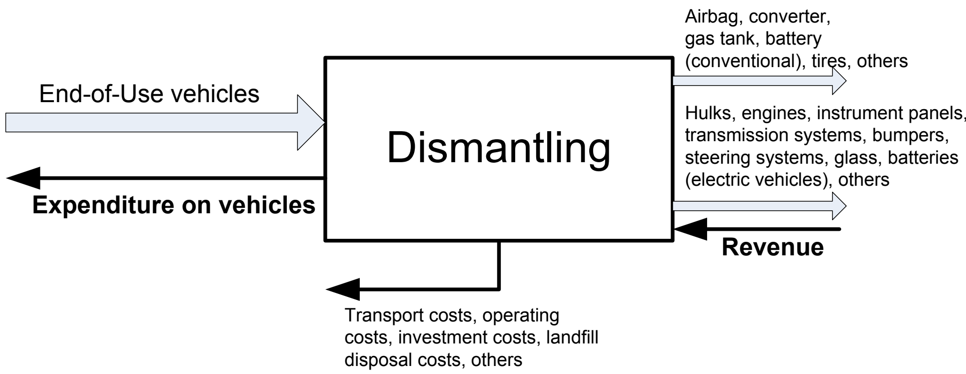

Figure 6: Profit calculation model for the dismantler

Table 4: Recycling fraction of materials and prices

Material	Recycling fraction	Price/Ton
Ferrous	0.95	100
Aluminum	0.90	750
Other nonferrous metals	0.75	1000
Plastics/composites	Varies	50
Others	0.5	50

5 MODEL RESULTS AND DISCUSSION

The graphs of Figures 7 and 8 show the impact of projected inventory changes - increases of hybrids and electrics - on the profitability of recycling business. Figure 7 shows the projected number of junked cars assuming conventional vehicles only (solid line) and the total inventory including hybrids (HEV) and electrics (BEV) (dashed line). It also shows the projected number of cars going to a landfill for both. Note the slight reduction in landfill due to the presence of smaller hybrids and electric vehicles.

Figure 8 shows the profitability trajectories for dismantler and shredder. Generally, the profits increase for the dismantler but decrease for the shredder once the hybrids and electrics enter the system. Interestingly, those graphs track the graphs for the conventionals. The dismantler would not be negatively affected by the material composition since this business depends on sale of components and the vehicle hulk. The increase in number of electrics could increase their end-of-life value since they would have batteries with reuse value. Currently, the market is still limited but assuming the market for batteries would become available, the dismantler could earn up to $47.00 per vehicle. The shredder, on the other hand, is largely affected by the material composition and weight of the automobile. Future vehicles are expected to be lighter but will have higher aluminum and plastic/composite content. Since aluminum is a more expensive material, the future profitability of this business would need to be evaluated further with different rates of increase of aluminum content.

6 CONCLUSION

The automotive recycling infrastructure in the U.S. has been driven by profitability. But, due to escalating cost of energy and fuel, conventional automobiles are becoming lighter and their material composition is also changing. Hybrids and electric vehicles are also projected to have a higher presence in the market. This will have an impact on the economic viability of automotive recycling business. In order to project the size of that impact, this paper has described a system dynamics model that can be useful to predict the future profitability.

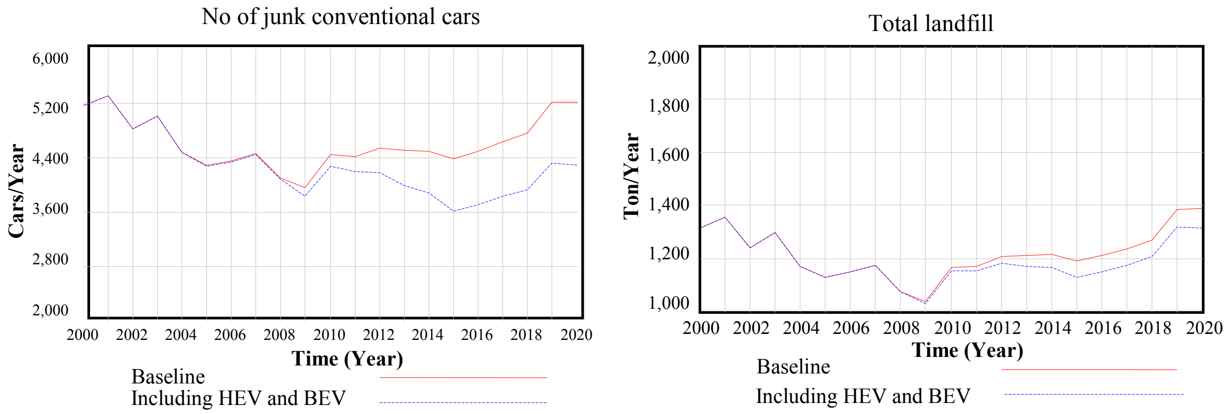

Figure 7: Number of conventional cars recycled and total landfill

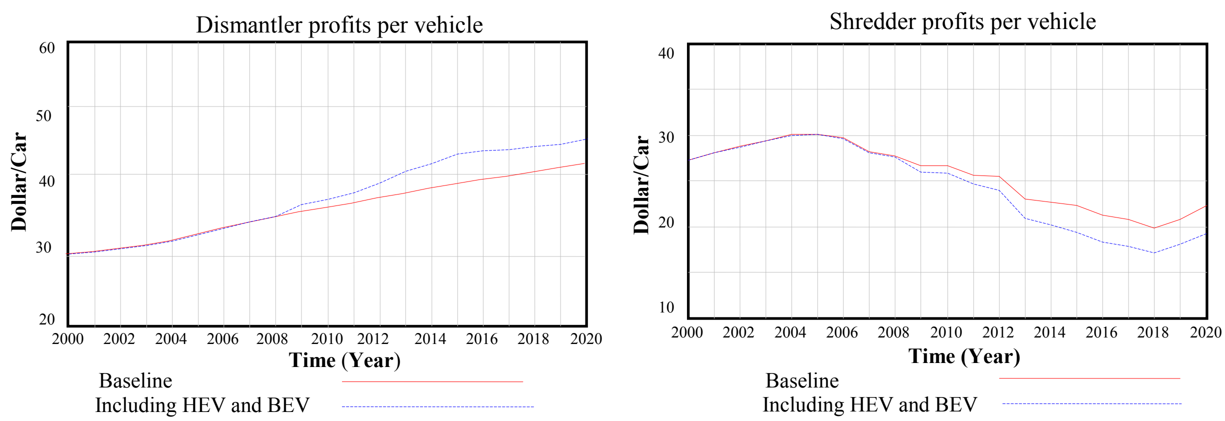

Figure 8: Dismantler and shredder profits per vehicle

Since this model is based on future projected data there is a possibility of inaccuracy in the data. Therefore, the usefulness of the model is not so much in foretelling what the profits of dismantler and shredder would exactly be as it is in determining their future trajectories. In this case, the dismantler profits would rise. But those of shredder business reduce in the short term because of reduction in automobile weight but would recover in the years ahead with further increase in the aluminum and other metals content.

As material composition of the automobile continues to change, technologies are needed to recover and recycle more plastics/composite materials. Otherwise, the automotive shredder residue (ASR) will increase. This would negatively affect the economics of the shredders as they will recover less material but pay more for landfill. It would also negatively affect the natural environment. Therefore, the recovery and recycling of plastics and composites is one of the major issues of interest. If technology can continue to be developed and matured to increase this recycling, the costs of recycling and subsequent profits would further the economic viability of investing in automobile recycling.

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DISCLAIMER

A number of software and other products are identified in context in this paper. This does not imply a recommendation or endorsement of the software products by the authors or NIST, nor does it imply that such software products are necessarily the best available for the purpose. A large part of this work was sponsored by the U.S. government and is not subject to copyright.

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