B. Baseline Assessment of Recycling Systems and Technology

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Objective

- Establish the baseline or state-of-the-art for automotive materials recovery/recycling technology.

Approach

- Review the state-of-the-art of worldwide automotive materials recovery/recycling technologies.
- Develop technology profiles of emerging automotive materials recycling technologies.
- Review international, federal, and state regulatory information regarding vehicle recyclability, substances of concern, and recycle laws and mandates.
- Conduct life-cycle studies to quantify the environmental burdens associated with various end-of-life recycling technologies.
- Conduct reference-case end-of-life recyclability studies.

Accomplishments

- Prepared a draft article that reviewed the state-of-the-art in recycling of vehicles and automotive materials.
- Conducted a literature search that identified mechanical, thermochemical conversion, and energy recovery technologies.
- Conducted life-cycle studies of selected alternative recycle technologies, including mechanical recycling and thermo-chemical conversion of shredder residue to fuels.
- Characterized the existing U.S. recycling infrastructure and derived estimates of automotive recycling rates from the literature.

- Conducted recyclability calculations for reference cases and three lightweight alternatives: lightweight steel, composite materials, and aluminum.

Future Direction

- Update the database of recycling technologies as new technologies emerge, a process that will include visits, as appropriate, to evaluate state-of-the-art material and energy recovery technologies in Japan and Europe.
- Continue life-cycle analysis and comparisons.
- Plan additional recyclability evaluations by using the current study as a starting point for assessing the recyclability of cars of the future.

Summary

The objectives of this project are to bench-mark the automotive materials recycling industry and to compile information in an accessible format regarding the status of existing and emerging recycling technology and research.

The focus of the work under this activity is (1) to develop the tools and document the information necessary to make effective decisions relative to technology needs to facilitate sustainable future vehicle recycling and (2) to make effective decisions regarding allocation of R&D resources.

The state-of-the-art of worldwide automotive materials recovery/recycling technologies and associated resource recovery infrastructures has been reviewed to identify technology gaps and needs and to identify differences in automotive recycling strategies in North America, Europe, and Asia. Technologies that are included in this review include, but are not limited to, post-shred materials recovery technologies, pre-shred materials recovery technologies, materials identification technologies, automated dismantling technologies, technologies for the recycling of specific components of vehicles (such as bumpers and fuel tanks), and thermochemical conversion technologies.

Life-cycle analyses of alternative recycle technologies have also been conducted to identify differences between technologies, such as mechanical recycling vis-à-vis thermochemical recycling, relative to energy and environmental benefits.

Regulations at the international, federal, and state levels are examined to identify the impact that proposed and existing regulations may have regarding recycling of automotive materials.

Reference-case recyclability calculations are made to quantify the expected recyclability of alternative vehicle designs.

Infrastructure

The North American recycling infrastructure has been characterized (Figure 1).

Technology Profiles

The recent literature has been reviewed, and summaries and profiles of available and emerging recycle technologies have been compiled into a draft working document and will be updated annually as new information becomes available.

A bibliography of abstracts of papers that discuss automotive recycling issues has been compiled. The bibliography is organized in the following sections:

- Recycling infrastructure,
- Design for recycling,
- Legal and regulatory issues,
- Life-cycle analysis,
- Research programs,
- Substances of concern,
- Disassembly technologies and case studies,
- Reuse of automotive parts and subassemblies,
- Remanufacturing,
- Mechanical separation technology,
- Thermochemical conversion technology,
- Energy recovery technology,
- Other technology,
- Advanced materials recycle technology, and
- Case studies of materials recycled for auto applications.

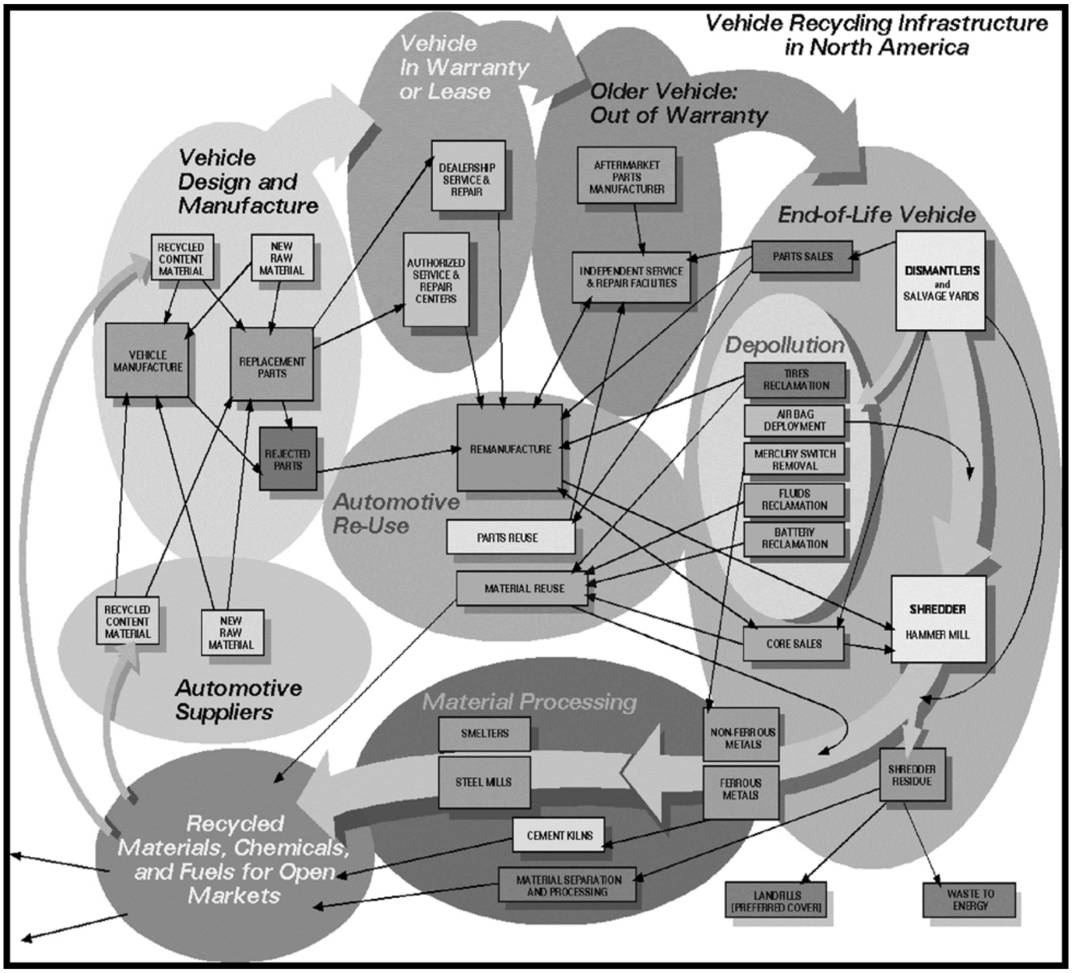

Figure 1. Representation of the North American automotive recycle infrastructure.

The bibliography was compiled from an extensive literature search, which included the following sources:

1. Society of Automotive Engineers (International) World Congresses from 1997 to 2004
2. Environmental Sustainability Conference and Exhibition, 2001
3. Society of Plastics Engineers:
   - ARC '98 Conference
   - ARC '99 Conference
   - ARC '00 Conference
   - GPEC 2002 Conference
   - GPEC 2003 Conference
4. Other conference proceedings:
   - International Automobile Recycling Congress 2001, 2002, 2003, 2004
   - TMS Fourth International Symposium of Recycling of Metals and Engineered Materials, 2000
   - Ecomaterials and Ecoprocesses, The Conference of Metallurgists, COM 2003

At present, the bibliography includes 196 citations (Table 1). References will be added to the bibliography as available.

Recycling Technologies: State-of-the-Art

A draft document describing the state of the art in recycling technologies for end-of-life vehicles, post-shred residue, and automotive materials has been prepared. Because post-shred residue contains residue from shredded white goods and other obsolete items (in addition to vehicles), these were also discussed in the document. The table of contents of this document is shown in Table 2.

Table 1. Citations included in the recycling bibliography (as of September 2005).

Bibliography Section	Number of Citations
Recycling infrastructure	18
Design for recycling	4
Legal and regulatory issues	24
Life-cycle analysis	9
Research programs	10
Substances of concern	5
Disassembly technologies and case studies	9
Reuse of automotive parts and subassemblies	1
Remanufacturing	0
Mechanical separation technology	21
Thermochemical conversion technology	12
Energy recovery technology	16
Other technology	36
Advanced materials recycle technology	7
Case studies of materials recycled for auto applications	24
Total citations	196

Regulatory Situation

The European Union has issued End-of-Life Vehicle Recycle Directives. The enforcement of these directives is, however, the responsibility of each member state. Although the United States has not developed a federal policy or mandate, regulations at the federal and state level can impact the technology needs for recycling automotive materials. For example, U.S. Environmental Protection Agency (EPA) regulations regarding polychlorinated biphenyl (PCB) limits the concentration of PCB on recycled materials to below the detectable limit (i.e., 2 ppm). State regulations regarding mercury and polybrominated diphenyl ethers (PBDEs) can also impede materials recycling.

Life-Cycle Studies

The objective is to use life-cycle analysis to assess the environmental impacts of various mechanical separation technologies and alternative end-of-life recycling technologies. This information will then be used to create a flexible, computerized, life-cycle inventory model, which is process-specific and yet can be modified to include additional recycling technologies and various material inputs. Life-cycle

Table 2. Draft state-of-the-art assessment table of contents.

1.0. Introduction and Background
2.0. The Process of Recycling Automobiles
- Dismantling for Direct Resale
- Shredding

3.0 The Process for Recycling White Goods
- Refurbishing of Units for Resale
- De-Pollution of the Units
- Shredding

4.0. Shredder Residue
- Composition
- Recycling of Materials from Shredder Residue

5.0. Technologies for Concentrating Recyclables from Shredder Residue
- Mechanical Separation Systems
- Gravity Separators
- Electrostatic Separators

6.0. Technologies for Separating and Recovering Products from Shredder Residue
- Argonne's Separation and Recovery of Flexible Polyurethane Foam
- Separation and Recovery of Plastics from Shredder Residue
    - Argonne's Froth Flotation Process
    - The RPI Process
    - The Salyp Process
    - The VW/SiCon Process
    - The Galloo Process
    - The MBA Process
    - The Toyota Process

7.0. Thermochemical Processes for Recycling Shredder Residue
- CWT Hydrolysis Process
- TPI Glycolysis Process
- Other

8.0. Energy Recovery from Shredder Residue
9.0. Substances of Concern
- Polychlorinated Biphenyls (PCBs)
- Heavy Metals
- Flame Retardants

10.0 Recycling of Advanced Vehicles
- Recycling of Fuel-Cell vehicles
- Recycling of Electric and Hybrid Vehicles
- Recycling of Aluminum and Magnesium from New-Generation Vehicles
- Recycling of Composites

11.0 Recycling of Other Vehicle Materials
- Catalytic Converters
- Tires
- Carpet
- Fluids
- Fuel Tanks

involves assessing all of the upstream burdens associated with the production of the materials and energies used in the process, including the transport of all materials to the facility.

PE Europe GmbH, a company that is experienced in conducting life-cycle assessments and in model development using its own GaBi (Ganzheitliche Bilanzerung) software, was contracted to perform these analyses. Two analyses have been done: one for Salyp NV's mechanical separation process and another for Changing World Technologies' (CWT's) thermal conversion process. PE Europe has also developed a flexible end-of-life model, and the model was used to compare the two different approaches to recycling shredder residue. The model allows the user to run simulations on shredder residue separation within different boundary conditions. The following boundary conditions can be modified: (1) shredder residue composition, (2) location of the facility, (3) type and distance of transportation, (4) market values for the separated fractions, (5) new potential applications for separated fractions, and (6) utilization ratio of the facility.

Salyp's separation process combined equipment developed by Argonne National Laboratory (ANL) and several others to create a facility that separates shredder residue into discrete fractions of metals, foam, mixed plastics, and fiber-rich and fines streams. On the other hand, the CWT process converts organic materials into hydrocarbon fuels and other potential products.

Primary data were collected for the Salyp and the CWT processes, including all energy, water, and material inputs, plus data on emissions to air and water, wastes, and products produced. both sets of data were entered into the GaBi software to create a flexible model of the process. Figure 2 illustrates the flow streams for the Salyp case.

In the case of the Salyp separation process, three different scenarios for handling the various materials recovered from shredder residue were determined. These scenarios included using specific material fractions as fuel for cement kilns (energy recovery), as well as using mixed plastics to replace such products as wood pallets and polypropylene (PP) pellets (material substitution). The various scenarios were assessed by using a variety of impact categories, including primary energy demand and CO_2 emissions. In the case of primary energy demand, all scenarios showed a net credit in total energy use. For the three scenarios studied, substituting recovered PP/polyethylene (PE) in a new PP application had the greatest benefit. However, if the mixed plastic stream was used to replace wood (e.g., decking material, park benches, wood pallets, etc.), the benefits to primary energy demand were less than if the recovered materials were simply used for energy recovery. In terms of CO_2 emissions, the PP application again showed the greatest benefit. Substituting PP for wood applications was next with a lower benefit, while the energy recovery scenario showed a negative impact on CO_2.

In the case of the CWT process, two basic scenarios were assessed. They involved using the light hydrocarbon oil generated by the process for fuel oil used in power plants to generate electricity and substituting light hydrocarbon oil for diesel oil (both with and without an added hot-oil processing step). While the oil product generated is more refined than an actual crude oil, it would require additional steps before it could be considered a true diesel oil. Therefore, reality is probably located somewhere between scenarios 1 and 2. In this study, the impact on primary energy demand resulted in a benefit in all cases. The benefits in the diesel substitution case were slightly greater than in the fuel-oil case. In the case of CO_2 emissions, all scenarios again showed an overall benefit. However, the diesel substitution case had a greater benefit than the fuel-oil substitution case.

A comparison of these two technologies is under way. Although early results show that the thermal conversion process has an overall advantage over the mechanical separation process, these results are heavily dependent on the assumed use of the end products in the life-cycle assessment, as well as on key assumptions on contamination and metals recovery. These factors are being addressed.

Recyclability Studies

Recyclability studies are being conducted to examine the effect of using automotive lightweighting material on recyclability. A

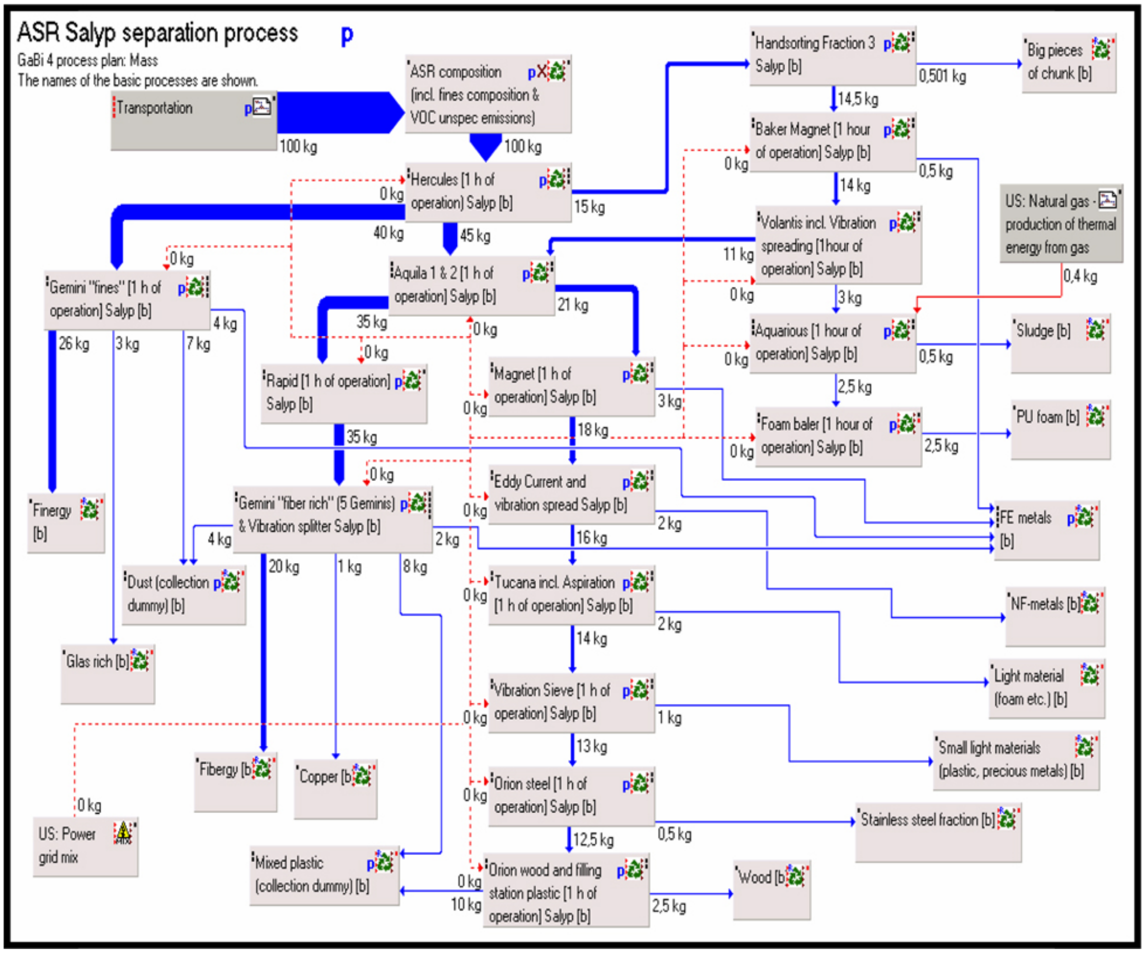

Figure 2. Life-cycle analysis mass-flow representation of Salyp separation process

Toyota Prius hybrid was selected as a reference case. This vehicle is a second-generation hybrid with a gas/electric powertrain. Evaluating the recyclability of this vehicle and its new technology will be a step in identifying changes that will impact end-of-life recycling of vehicles of the future.

In collaboration with Johnson Controls, Inc. (JCI), the VRP dismantled the vehicle according to VRP procedures to single material components and entered data for each part into a database. A material list that identified the breakdown of materials into separate classifications (such as ferrous and non-ferrous metals, as well as composite materials and plastics) was prepared. The materials breakdown is summarized in Table 3. In comparison, the materials composition of a production Ford Taurus is summarized in Table 4.

Table 3. 2004 Toyota Prius materials breakdown.

Materials	Mass (kg)	Percent
Ferrous metals	776.94	60.55
Nonferrous metals	229.99	17.92
Plastics	154.85	12.07
Elastomers	39.66	3.09
Inorganic material	34.71	2.71
Other	28.21	2.20
Organic materials	18.84	1.47
Vehicle mass (less fluids)	1,283.1	100.00

Three different recyclability calculations were made (Table 5). The Federal Trade Commission (FTC) recyclability number is the percentage by weight of the material that is currently being recycled, and it includes metals, fluids less fuel, and batteries. The

Table 4. 2004 Ford Taurus materials breakdown.

Materials	Mass (kg)	Percent
Ferrous metals	1,008.28	70.37
Plastics	154.41	10.78
Nonferrous metals	141.43	9.87
Elastomers	68.71	4.80
Inorganic material	40.91	2.86
Other	17.45	1.22
Organic materials	1.66	0.12
Vehicle mass (less fluids)	1,432.86	100.00

Table 5. Reference case recyclability: 2004 Toyota Prius.

Calculation Method	**Recyclability (%)**
Federal Trade Commission	80.86
European	97.61
Feasibility of recycling	85.58
Ref. 2000 Ford Taurus	80.50

European guidelines include FTC materials plus fuel at 90% of a full tank, plastics that could be recycled, and up to 10% by weight energy recovery. Note that Europe requires 95% recyclability for new vehicles. The feasibility-to-recycle number includes the FTC materials plus plastics that can be recycled. Changes to the current infrastructure would be required to increase recycling beyond the current FTC percentage.

To establish an indication of the impact of lightweight materials on the reference case recyclability calculations, the 2004 Toyota Prius is compared with a proposed aluminum-intensive lightweight vehicle and a proposed composite lightweight vehicle, both of which are also based on the 2004 Prius. The production 2004 Toyota Prius hybrid vehicle body was steel with an aluminum hood and decklid. The suspension was of steel, except for an aluminum steering knuckle on the front suspension. This vehicle was used as the base for this study.

The aluminum alternative is for a 2004 Toyota Prius with an aluminum body and a magnesium engine cradle and a rear axle substituted for the production parts. In addition, seat frames, body brackets, and the instrument panel cross car beam have been changed from steel to aluminum. As a result, the weight has been reduced by approximately 630 lb or 21%. Because the weight reduction is entirely in the currently recycled portion of the vehicle, the recyclability is adversely affected and is reduced from 80.86% to 76.10%. No changes were made to the currently- nonrecycled portion of the vehicle. Aluminum replaced steel at 50% by weight of the original steel.

The composite alternative is for a 2004 Toyota Prius that consists of (1) a carbon-fiber body with 40% carbon fiber and 60% thermoset polyurethane/urea resin by volume, 49.72% carbon, and 50.28% thermoset polyurethane/urea resin by weight and (2) a magnesium engine cradle and rear axle substituted for the production parts. In addition, seat frames, body brackets, and the instrument panel cross car beam have been changed from steel to composite. As a result, the weight has been reduced by approximately 711 lb, or 24%. Because the weight reduction is entirely in the currently recycled portion of the vehicle, the recyclability is adversely affected and is reduced from 80.86% to 57.20% if none of the composite is recycled or 74% if all of the composite material is recycled. No changes were made to the currently nonrecycled portion of the vehicle. The composite material replaced steel at 40 wt% of the original steel.

There are reductions in all three recyclability calculations for lightweighted vehicles, even though the rest of the vehicle is not changed (Table 6). Where the aluminum and composite material is being recycled, the same amount of material would be disposed of in landfills in each of the three scenarios. The only difference is that the recycled portion of the lightweighted vehicles would be lighter. Although the recyclability would be less, there would be no difference in the amount of material disposed of in landfills, and the lighter vehicles would use less fuel during their life. As can be seen, lightweighting presents challenges in the European market. Note that these calculations do not take into account the downsizing of related components that would accompany any lightweight vehicle, such as powertrains, brakes, and tires. Because the downsized components are high in metallic content, downsizing will further reduce recyclability and make it difficult to meet the European 95% requirement.

Table 6. 2004 Toyota Prius recyclability, reference case vs. aluminum and composite body materials.

Calculation Method	As Produced (%)	Aluminum Body (%)	Composite Body (%)
FTC	80.9	76.1	74.0[a]
European	97.6	96.0	94.5[a]
Feasibility of recycling	88.3	85.6	83.9[a]

[a] If the composite material were not recycled, then the numbers would be FTC, 57.2%; European, 78.2%; and feasibility of recycling, 67.1%. Recycling of the composite material would require significant changes in the current recycling infrastructure. In addition, a market for the recycled carbon fibers would need to be developed. Current technology for recycling carbon fibers results in a 20% loss in fiber properties and would limit their reuse to short-fiber applications.

In conjunction with this study, additional evaluations are planned by using these data as a starting point for assessing the recyclability of cars of the future. The impact of vehicle lightweighting and material selection on recyclability will be evaluated. In addition, the impact of powertrain changes in future vehicles (including hybrid and fuel-cell alternatives) on recyclability will be determined in comparison to powertrains in current vehicles. An assessment of various alternatives on recycling and the effect on the current recycling infrastructure will be produced. No downsizing of other components was included in this study. Future studies will reflect the downsizing of powertrains, brakes, tires, and other components in recyclability calculations. Items requiring further study resulting from these assessments will support future projects to determine the feasibility of various alternative vehicle configurations and choices of materials.

These results demonstrate the need for technology to recycle new automotive material if recycling mandates are to be met and to ensure that lightweighting materials are not excluded because of the inability to recycle them.

Publications

Modular Life Cycle Model — Basis for Analyzing the Environmental Performance of Different Vehicle End-of-Life Options, Binder, M.; Simon, N.L.; Duranceau, C.M.; Wheeler, C.S.; Winslow, G.R., Proc. of the 5th International Automobile Recycling Congress, Amsterdam (Mar. 9-11, 2005).

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United States National Life Cycle Inventory Database Project, A Status Report, Sullivan, J.L.; Wheeler, C.S.; and Simon, N.L., SAE Paper 2005-01-0852.