A global perspective on the environmental challenges facing the automotive industry: state-of-the-art and directions for the future

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Abstract: With support from the US National Science Foundation and Department of Energy, a global benchmarking study of the status of Environmentally Benign Manufacturing (EBM) has recently been completed. The study [1], completed under the aegis of the World Technology Evaluation Center at Loyola College in Maryland, gathered information on research and development around the world aimed at developing alternative methods for materials processing with the purpose of minimizing toxic material generation and optimizing products and by-products for sustainability and reuse characteristics. The study reviewed the current status of EBM research, development, and applications in the United States, Japan, and Europe with a view towards evaluating the competitive status of US efforts. Information was acquired from the technical literature as well as through visits to industry, national laboratories, universities, etc. One area of focus within the study was the automotive industry. This paper summarizes many of the key findings from the global benchmarking study that relate to the automotive industry and identifies areas that require attention for the future.

Keywords: Automotive industry, benchmarking, design, emissions, engine, environment, manufacturing, materials, post-use, powertrain, recycling, regulations.


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1 Introduction

Automobile usage is increasing in the US and elsewhere in the world. There were 700 million motorized vehicles registered in the world in 1999, with the US itself contributing over 200 million passenger cars and light trucks [2]. In the 1990s the number of cars worldwide grew three times faster than the human population [3] and the number of US cars increased six times faster than the population from 1969 to
1995 [2]. The situation in Europe is also of concern. For example, the Copenhagen-based European Environment Agency (EEA) stated in their recent report on the ‘State of the European Environment’ that transportation presents a huge threat to the environment as increases in freight and passenger vehicle use threaten climate change and air pollution goals. In fact, the EEA has stated that more efficient engines may not be enough to offset shifts towards larger cars, increases in car and air travel, and increases in distance driven per person [4]. While automobiles are presently too expensive for most people in developing nations, this situation may change with the increasing standard of living in such nations as India and China. All these facts point to the importance of environmental issues as they relate to the automotive industry.

The auto industry and its suppliers are aware of the ever increasing need to address environmental issues in their products and processes [5]. Many of the companies within the industry are very large global corporations (GM, Ford, Toyota, and DaimlerChrysler) that are well informed about technological, sociological, and legal trends across the globe that are calling for improved environmental performance [6]. As part of the global benchmarking Environmentally Benign Manufacturing (EBM) study, all of these referenced organizations were visited as well as several of their key Tier 1 suppliers and others in the vehicle industry. Every organization that was visited had some sort of environment-related company program/initiative, although these initiatives differed in their scope and focus. Differences were evident across countries as well as within the supply chain. In fact, one of the biggest differences evident from this study was not the company-to-company differences, but the differences in public attitudes toward the environment from country-to-country. Since the public makes up the work force of companies, the environmental awareness differs even within the same company as one moves from one country to another. Given this background, a number of the ongoing environmental improvement efforts that are being undertaken by companies within the automotive industry are presented.

The environmental issues associated with the automotive industry may be discussed in terms of the life cycle stages of an automobile. A typical life cycle is shown in Figure 1. In the figure, four principal stages are presented: i) materials

![Automobile life cycle](image)
processing, ii) manufacturing, iii) use, and iv) post-use. The materials processing and manufacturing stages are largely concerned with creation of a finished product. The use stage considers the actual use of a product, in this case the operation of a vehicle. The post-use stage of the product includes both product recovery as well as its subsequent disposition via reuse, remanufacturing, recycling, or disposal.

Before examining the efforts around the globe that are directed at improving the environmental performance of automotive products and processes, it is useful to examine the current status of the industry. Under the umbrella of USCAR (United States Council for Automotive Research), the United States Automotive Materials Partnership Life Cycle Assessment group (USAMP/LCA) completed an LCI (life cycle inventory) of a generic US mid-size vehicle [7]. For each part within the vehicle, the material type and mass were identified. The generic vehicle had a mass of 1523 kg, used gasoline as a fuel source, had a fuel efficiency of 10.23 L/100 km (23 mpg: miles per gallon), and had a service life of 193 000 km (120 000 miles). For each stage in the life of the vehicle environmental data were collected, for example, energy usage, water consumption, air emissions, water emissions, solid wastes, and raw materials consumption. Key findings of the LCI include:

- The generic vehicle’s ‘use’ phase dominates the vehicle’s energy consumption.
- The material production and manufacturing stages contribute 14% of the consumed energy, 65% of the particulate emissions, 67% of the solid waste, and 94% of the metal waste to water.
- The end-of-life phase contributes 8% of the total life cycle solid waste, primarily as automotive shredder residues (ASR).

Similar studies have also been performed on Japanese and European generic vehicles producing comparable findings [8,9].

While the EBM study is primarily concerned about the environmental issues surrounding manufacturing processes/systems, it is nearly impossible to address the environmental concerns of the automotive industry without at least a brief discussion of the product itself. As a result, each of the life cycle stages will be addressed in the sections that follow. In addition, a section has been provided that addresses more system oriented issues, e.g., supply chain challenges. Findings from the technical literature will be reported, as will information from site visits in Japan, Europe, and the US. The paper will conclude by identifying industry-wide trends and need areas.

2 Material issues

Material selection plays a critical role in the environmental performance of automotive products. An automobile is a complex product that consists of a number of systems and material types. As part of the USAMP LCI activity, Sullivan et al. [7] tabulated the material composition of a generic mid-size US automobile. Figure 2 displays the breakdown of the materials within the vehicle. As is evident, ferrous materials (cast iron and steel) make up nearly two-thirds of the total vehicle weight. However, this fraction has reduced significantly over the last several decades as lighter materials (aluminum and plastics) have begun to supplant the use of ferrous materials.
In considering the selection of materials, Graedel and Allenby [8] advocate the use of the following guidelines for the design of industrial products:

- Select nontoxic and abundant materials.
- Select natural materials (e.g., cellulose) rather than artificial substances (e.g., chlorinated aromatics).
- Select materials that are easy to recycle.
- Minimize the variety of materials used in products and processes.
- Acquire materials via a recycling stream.

The automotive industry utilizes a tremendous amount of material resources, and a summary of the amount of various types of materials within an automobile are given in Table 1. The first of the guidelines indicates that materials should be used that are abundant, and since iron and aluminum are plentiful in nature, they satisfy this criterion. Other listed metals are less common. Fluids (e.g., oil and transmission fluid) and rubber are petroleum derivatives and are therefore subject to the same scarcity as this limited natural resource. The table also lists the fraction of the total

**Table 1** Amount of various material types used in an automobile and their usage as a percent of the total US consumption (adapted from [10])

<table>
<thead>
<tr>
<th>Material</th>
<th>1950s automobile (kg)</th>
<th>1990s automobile (kg)</th>
<th>% of total US consumption used in 1990 automobiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastics</td>
<td>0</td>
<td>101</td>
<td>3.2</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0</td>
<td>68</td>
<td>18.9</td>
</tr>
<tr>
<td>Copper</td>
<td>25</td>
<td>22</td>
<td>10.0</td>
</tr>
<tr>
<td>Lead</td>
<td>23</td>
<td>15</td>
<td>69.5</td>
</tr>
<tr>
<td>Zinc</td>
<td>25</td>
<td>10</td>
<td>23.0</td>
</tr>
<tr>
<td>Iron</td>
<td>220</td>
<td>207</td>
<td>34.5</td>
</tr>
<tr>
<td>Steels</td>
<td>1290</td>
<td>793</td>
<td>13.5</td>
</tr>
<tr>
<td>Platinum</td>
<td>–</td>
<td>0.002</td>
<td>41.4</td>
</tr>
<tr>
<td>Rubber</td>
<td>85</td>
<td>61</td>
<td>62.9</td>
</tr>
<tr>
<td>Glass</td>
<td>54</td>
<td>38</td>
<td>–</td>
</tr>
<tr>
<td>Fluids</td>
<td>96</td>
<td>81</td>
<td>–</td>
</tr>
<tr>
<td>Other</td>
<td>83</td>
<td>38</td>
<td>–</td>
</tr>
<tr>
<td>Total</td>
<td>1901</td>
<td>1434</td>
<td>–</td>
</tr>
</tbody>
</table>
US consumption that is used by the automotive industry. As is evident, the autoindustry is the primary consumer of such materials as lead, platinum, and rubber.

Table 1 indicates that the relative use of ferrous materials has droppedsignificantly since the 1950s. The key to understanding the motivation for reducingthe use of ferrous materials in an automobile is the fact that the replacementmaterials have a lower mass density, and mass reduction is a proven method forobtaining improved vehicle fuel economy. As an approximation, a 10% reduction inmass produces a 5% improvement in fuel economy. Over the last 25 years, as USautomakers have responded to government-mandated CAFE (Corporate AverageFuel Economy) requirements, they have turned to lighter materials such as aluminumand plastics. Magnesium, polymer composites, and ceramics are also being favorablyviewed as automotive components. Graedel and Allenby [10] suggest that thefollowing material types are expected to play an increasingly important role in thevehicle of tomorrow:

- Engineered plastics: Lower costs and improved material performance will resultfrom advances in processing technology. The total quantity of plastics in thevehicle may double – essentially eliminating non-plastics in vehicle interiors. (Oneof the organizations that was visited, Johnson Controls, is making effective use ofrecycled PET plastic in its headliner substrate.)
- Composites: Organic and inorganic fibers that are woven together andimpregnated with a plastic resin can be five times lighter than metals andprovide competitive strength. (In partnership with the German government,DaimlerChrysler is working to use natural fibers, e.g., sisal and flax, instead ofglass fibers in fiber-reinforced plastic vehicle components. The challenges of thiseffort include the lack of an existing transportation infrastructure and thevariation in fiber quality introduced by weather conditions, processing, drying,etc.)
- Ceramics: These materials can be light and retain their hardness at hightemperatures. Advances in formulations and in processing techniques will allowthese materials to find application as engine components. (As an example,DaimlerChrysler and its suppliers are working to develop a successful siliconnitride ceramic engine valve.)
- Light Metals: As noted, aluminum is already widely used in automotiveapplications. Magnesium usage is growing because its density is 25% of steel’s and67% of aluminum’s. Factors limiting the widespread use of magnesiuminclude its cost, availability, lack of suitable manufacturing technology/knowl-edge, and the susceptibility of the material to corrosion. (To support its growingneed for magnesium, Ford is investing in the growth of Australia’s magnesiummining industry.)

Of course, material selection guidelines suggest that toxic/hazardous materialsshould be avoided in products and processes. Each US auto-maker has developed a list of permissible materials that may be used by their vendors. These specificationsare aimed at minimizing the introduction of hazardous materials that increase theregulatory burden of plants, result in the generation of hazardous waste requiringexpensive management, or result in the release of chemicals that must be reportedunder the US EPA’s Toxics Release Inventory (TRI). European-based companies
likewise have established ‘black-lists’, materials that are to be avoided in their products and processes, and ‘gray-lists’, materials that are to be avoided unless no viable substitutes are available. Japanese companies are also working with their suppliers to ensure that hazardous materials are avoided. (Toyota’s 1999 Environmental Report notes that Environmental Purchasing Guidelines have been distributed to 450 suppliers of parts and materials in March 1999. These guidelines call for supplier ISO 14001 certification by 2003 and control of substances of environmental concern.)

The ease with which a material can be recycled is another guideline that should be considered when making material selection decisions. Steel and aluminum may be recycled relatively easily, although it has been suggested that these materials may only undergo several recycling loops until contaminant levels are too high to produce acceptable microstructures without additional purification steps. The recycling loops associated with other metals, e.g., lead and copper, are also fairly well established. A by-product of the automotive metal recovery recycling process, automotive shredder residue (ASR) is largely composed of contaminated polymer materials. At present, ASR is often landfilled in the US since polymer separation technologies cannot generally produce materials that are cost effective when compared to virgin resins. There are several examples where ASR has been used as a fuel source. The bottom line, however, is that in the absence of regulatory intervention automotive plastics are not being recycled to a great extent. Since it is envisioned that efforts to further reduce vehicle weight will result in an increased fraction of plastic and composite components, this may hamper future recycling efforts. Reduced metal content may jeopardize the economic viability of the current vehicle recycling infrastructure, thus endangering the recovery rate of material resources at vehicle end-of-life.

3 Manufacturing issues

A key stage in the life cycle of an automobile is the creation of the vehicle itself from engineering materials. An automobile may be broken down into the following subsystems: powertrain, suspension, HVAC, electrical, body, and interior. The production of components for these systems involves a wide range of manufacturing processes (e.g., casting, compression molding, machining, forming, adhesive joining, welding, coating, painting, injection molding, fiber/textile manufacturing, glass production, cleaning, and assembly). To place the manufacturing stage in the context of the life cycle for the whole vehicle, Sullivan et al. [7] report the following:

- The material production and manufacturing stage constitutes 14% (about 140 GJ) of the total vehicle life cycle energy demand of a generic vehicle. On its face, this suggests that manufacturing energy requirements constitute a minor portion of the overall energy demand compared to the use portion of the life cycle that consumes 84% of the energy. However, it must be noted that the energy consumed during vehicle use is distributed over a 10–15 year period, while the manufacturing energy demand (and concomitant CO2 production) occurs over a much smaller time period.
- 65% of the airborne particulate and 94% of the water-borne metals are generated during the material production/manufacturing stage of the life cycle.
67% (about 2800 kg) of the solid waste is produced during the material production/manufacturing life cycle stage. Figure 3 shows the distribution of solid waste across three stages of the life cycle.

It should be reiterated that the energy/wastes associated with the manufacturing life cycle stage tend to be more temporally and spatially concentrated than the energy/wastes associated with the use stage.

There are significant differences in the energy efficiency and the relative quantity of waste produced across the whole range of manufacturing processes. This EBM study revealed that there are also substantial differences in attitudes towards energy consumption and waste. These differing attitudes towards the environment were less a function of the company and more dependent on the sociopolitical climate of the sites that were visited:

- Industries in Japan are highly focused on the reduction of energy needs and CO₂ emissions. This attitude is perhaps motivated by the cost of meeting energy requirements through imports and the need to comply with the Kyoto Protocol. Solid waste reduction is also a priority. Again, this is motivated principally by specific Japanese factors: the small area of the country and thus rapidly diminishing space for landfills. (Japanese agricultural machinery manufacturer Kubota indicates that their ability to minimize waste and utilize energy efficiently is a key to their long-term economic competitiveness.)

- In Europe, industry is very concerned about end-of-life products. This concern is prompted by the lack of available landfill space and the prominence of environmental political movements. (According to one German consulting company, GUA (Gesellschaft für umfassende Analysen), recent European legislation, issued in Germany, Austria, Switzerland, Scandinavia and the Benelux countries, stipulates that virtually no organic carbon shall be disposed in landfills. A typical regulation is to restrict the content of total organic carbon in all landfill materials to 5% by weight. This goal can only be reached through significant waste incineration. The majority of the European public now believes that waste incineration is less harmful to the environment than landfilling.) Leadership in terms of meeting ISO 14000 standards may also provide short term market protection for European industry.

- Attention by US industry appears to be largely centered on compliance with government regulations that are principally directed at reducing/eliminating toxic discharges. The abundant supply of inexpensive energy and landfill space (in most of the US) provides little economic incentive for pursuing non-regulatory driven environmental initiatives. (Several US automakers have plants in Mexico.)

![](https://example.com/figure3.jpg)

**Figure 3** Solid waste for three life cycle stages for a generic mid-size US automobile [7]
that are zero wastewater producers. At these locations where the water supply is limited, there is economic incentive to minimize water usage, and thus water discharges are recovered and recycled.

Based upon all the site visits and a review of the technical literature, environmental concerns have been identified for the following manufacturing processes:

- Casting
- Sheet metal working
- Glass manufacturing
- Painting/coating/plating
- Machining
- Joining
- Plastics processing
- Part washing

A brief discussion of the environmental challenges associated with each of these processes is described below.

### 3.1 Casting

Figure 3 indicated that about 2800 kg of solid waste is produced in the materials processing/manufacturing life cycle stage for a generic vehicle. As part of another LCI study, Rogers [11] partitions the purely manufacturing-related waste (totalling about 860 kg/vehicle) as shown in Figure 4. As is evident much of this waste may be termed ‘engineered scrap’, i.e., material built into a part that must subsequently be removed through processing. Examples of this type of scrap include the gates, risers, and sprues that are produced in casting processes. Casting sand represents another large solid waste contributor (about 120 kg/vehicle or 2 million tons/year for the US automotive industry). Used foundry sands contain organic binders and heavy metals that could leach out upon disposal, and thus must be treated as hazardous waste. Casting processes also produce airborne emissions of environmental concern (NOx, VOCs, etc.). For non-ferrous metals, die casting is a widely utilized process, and the wastewater produced by die cooling represents an environmental improvement.

![Figure 4](MfgSolidWaste.png)  
**Figure 4** Sources of manufacturing waste for a generic US vehicle [7]
opportunity. Lost foam casting (expendable pattern casting) is another frequently employed operation, and the airborne emissions from the process are receiving increasing scrutiny.

To lower the environmental impact of casting processes [12], the quantity of parting and cooling agents should be curtailed. More benign expendable pattern materials should be investigated. Also of interest would be new uses for spent foundry sands and/or new casting methods that utilize reusable or recyclable materials. Avenues for reducing casting energy requirements should be pursued. (To reduce casting process energy requirements, Japanese manufacturer Kubota has replaced their gas dryers with microwave dryers for the drying of core coatings.) Finally, and perhaps most importantly, there is a need to improve casting process accuracy/precision so that net shape products can be produced, thus avoiding subsequent downstream processes.

3.2 Sheet metal working

Another source of the ‘engineered scrap’ highlighted in Figure 4 is sheet metal working operations. For example, in stamping processes, typically 40% of the metal ends up as scrap. Research is needed into sheet metal forming processes that will reduce scrap production. To achieve higher vehicle energy efficiencies lighter and thinner sheet materials will be employed. Since designers/manufacturers have less experience with these materials, research is needed to support their use in automotive applications. New processing technologies such as hydroforming and superplastic forming offer environmental advantages and merit continuing investigation as does the processing of Tailor welded blanks.

3.3 Glass manufacturing

Automotive glass manufacturing is the process with the largest energy consumption per kilogram of product (approximately 1 MJ/kg according to the US Department of Energy Glass Industry Roadmap). The production of virgin glass is more energy intensive than the production of recycled product. For both cases, glass production requires large amounts of energy (acquired via carbon-based fuel sources) and results in significant CO₂, NOx, and SOx emissions. Composition, coating, and tempering improvements along with improved process control can reduce the quantity of manufacturing pieces rejected and thus reduce overall energy consumption. (According to USCAR’s Vehicle Recycling Partnership, while the technology exists to recycle automotive windshields, at present it is not economically feasible. It currently costs more to recover windshields for the recycling infrastructure than it does to send them to landfills. About 3% of ASR is associated with the windshield.)

3.4 Painting/coating/plating

Historically, the set of processes (including coating and painting operations) used to produce an appealing finish for the vehicle body has resulted in the largest per vehicle emissions of Volatile Organic Compounds (VOCs) and Hazardous Air Pollutants (HAPs). These emissions are being reduced as automakers transition from oil-based
paints to water-based paints. Research appears to be progressing on the development of powder or slurry paint applications, that are superior to oil- and water-based paints in terms of emissions. One of the principal challenges of powder paints is achieving an acceptable surface quality. It is estimated that the energy requirements for painting and its associated processes account for over 50% of the energy consumption in an assembly plant. Germany and the US appear to be the leaders in the development of new paint technologies, with Japan placing less emphasis on airborne emissions. The range of paint technologies that are being used across the industry is very large, and the degree of control being exercised on airborne emissions is also highly variable from plant to plant. As with any new technology, much work remains to identify successful operating conditions; in this case, conditions that produce finishes that are attractive to the consumer.

GM researchers identified steel pre-coating as one desirable solution to some of the painting-related concerns. Steel coils delivered in a coated/primed form may offer the following advantages: improved corrosion resistance, reduced environmental burden, reduced paint shop investment, lower losses to rust/stain, and reduction in stamping process lubricants. Of course, the use of pre-coated/primed steel sheet in lieu of painting has a number of technical challenges: development of appropriate coating formulation, suitability for welding and forming operations, corrosion protection, adhesion properties, color matching, and compatibility with existing systems.

Historically, heavy metals such as chromium and nickel have been used to prepare decorative coatings, e.g., chrome bumpers. These coatings are applied through a plating process in which the part is immersed in a series of baths. Metal plating plants can release a variety of toxic compounds. Chlorinated hydrocarbons may be emitted during pre-cleaning (degreasing) of metal parts, and caustic mists, cyanides, and metals are released from the actual electroplating process. Hexavalent chromium, a carcinogen, is of particular concern for worker and public exposure. Development of better emission containment and recovery are priorities here for existing processes. Also, research needs to be completed into less hazardous coating materials.

**3.5 Machining**

Machining processes (e.g., milling, boring, grinding, and drilling) are inherently wasteful in that their purpose is to remove material from a component (engineered waste). However, at present, there are few alternatives to machining in terms of producing acceptable dimensional accuracy/precision and surface finish. Chips or debris produced by machining operations are routinely recycled assuming they have not been contaminated with other materials or cutting fluids (contaminated chip disposal is an expense while uncontaminated chip recycling is a revenue). Metalworking fluids are commonly used for lubrication, cooling, chip flushing, and part corrosion protection in machining operations. Metalworking fluid mists are a recognized occupational health hazard [13,14]. Dermal exposure to cutting fluids may cause a variety of skin ailments. These facts highlight the importance of mist control and industrial hygiene considerations. Research is needed on the advancement of improved mist collection/control/air handling strategies and worker
protection systems [15], including the development of fluids that are less prone to aerosol formation [16] or that do not represent an inhalation hazard.

The disposal/treatment cost of used fluid is high, as are the other fluid-related costs (fluid recirculation, mist handling, maintenance, etc.). Recent European studies [17] report that these costs may constitute 10–20% of the total costs in some production plants. While these costs are somewhat less in the US, the costs and health-related liabilities do point out the growing importance of decisions regarding metalworking fluids. The degradation and therefore rate of disposal of metalworking fluids can be accelerated by improper fluid maintenance (failure to control bacteria growth, tramp oils, contaminants, etc.). Thus, work is needed to establish appropriate fluid system maintenance procedures and develop fluids that are robust to contaminants and slow to degrade. The development of better fluid recycling technologies is also a priority.

Another approach to reducing the environmental problems associated with cutting fluids is to stop using them, i.e., employ dry machining. Dry machining avoids many of the costs previously noted associated with the use of cutting fluids (and also has positive environmental and health effects). Several materials have been traditionally cut dry (e.g., cast iron), and research is underway on the development of technologies/strategies to achieve dry machining for more ductile materials such as aluminum. In the drilling and tapping of aluminum, cutting fluids provide lubrication that under dry conditions must be achieved by other means (new cutting tool coatings for example). While not completely dry, MQL (minimal quantity lubrication), i.e., the application of fluid at very low flow rates, is being pursued by both machine tool builders and end users. In the absence of a cutting fluid, issues such as heat transfer from the workpiece and chip flushing must be given special consideration.

Machine tool builder EX-CELL-O (Eislingen, Germany) is developing new machine tool concepts where chips are allowed to fall through the center of the machine onto a chip conveyor (rather than off the front or rear of the machine). They are also working to standardize the heights of their machines to make them more interchangeable. EX-CELL-O is also a leader in the development of MQL technologies, where nearly dry machining is achieved by applying cutting fluid at rates in the order of ml/hour. They also indicated that for dry or nearly dry machining, the management of heat in and around the machine tool is absolutely essential to avoid workpiece thermal distortion problems. At the 1999 National Center for Manufacturing Sciences Fall Workshop, several machine tool builders expressed concern over the long term reliability of machine tools in the absence of cutting fluids. It was indicated that the dust/chips produced under dry conditions could accelerate the wear rates of machine tool components.

3.6 Joining

Joining operations (including adhesive bonding and welding) produce a variety of wastes and can consume considerable amounts of energy. With adhesive bonding, epoxy resins may be used to join metallic or non-metallic materials to one another. Some of these adhesives generate VOCs and produce other airborne contaminants. Components that are to be joined via an adhesive bond often require some surface
preparation (e.g., cleaning and degreasing) to ensure adequate/intimate contact between the adhesive material and the components – also having an environmental consequence. Mechanical joining uses physical means to hold components together (e.g., screws and bolts). The environmental effects of such operations are largely associated with the energy required to perform the operation and the manufacture of the fasteners. It may be noted that unlike many other joining methods, mechanical joining operations can often be reversed, which may offer some environmental advantage in terms of product recycling/remanufacture.

Welding processes are some of the most common joining operations, and in fact, resistance spot welding is the predominant means of joining sheet metal in auto body manufacturing. Welding operations can produce the following emissions: carbon monoxide, nitrogen oxides, ozone, dusts, and metallic fumes. The airborne particulate matter may include: lead, cadmium, cobalt, copper, manganese, silica, and fluoride compounds. Additional wastes that may be generated include used filler rods and electrodes, heat, and electromagnetic radiation (possibly resulting in retinal damage). The US National Institute for Occupational Safety and Health [18] has reported a number of health-related concerns associated with welding. Control of welding generated HAPs is clearly a priority, and the auto industry appears to be managing this concern effectively. Reducing the amount of welds (where possible) will reduce energy consumption and process wastes. Also desirable is research focused on improving welding technology for aluminum.

3.7 Plastics processing

Many of the environmental challenges of plastics/polymer processing lie within the chemical industry rather than the automotive industry. However, several comments are provided about plastics processing relative to the automotive industry. Plastics processing (molding, extruding, etc.) generally requires large amounts of externally applied energy, though there are some recent innovations such as reaction injection molding, where heat is supplied by an exothermic reaction. The use of recycled plastics in automotive components is challenging due to the large number of polymer formulations and additives, and also because the polymer molecules degrade as they are reprocessed. Thermosets (commonly used in engineering applications and particularly in the electronics industry) present another problem in that they cannot be recycled. The use of polymer foams offers significant benefits in terms of weight reduction, although the blowing agent may represent an environmental concern. Polymer processing operations can produce contaminated wastewater, and under the high heat and pressure associated with molding processes, HAPs may be produced.

3.8 Part washing

In the past, solvents were often used to clean components, i.e., remove grease, dirt, and other foreign matter. To reduce HAPs (specifically VOCs), large manufacturers have moved to aqueous cleaning methods that are performed at elevated temperatures/pressures often under acid/basic conditions. The wastewater produced during these cleaning operations represents an environmental concern and requires treatment. The energy consumed by the process is also an issue that has received little
attention. Finally, the process is an aerosol source and little is known about the composition and therefore the health effects of the airborne particulate produced by such operations. Of course, actions should be pursued that can eliminate processes such as part washing that add no value to a part and generate environmental and worker health concerns.

In closing, it should be noted that automobile manufacturers are large, sophisticated global corporations. They follow one another very closely and quickly adopt new technologies if they offer economic/competitive advantages. However, the environmental landscape is changing quickly around the world, and failure to achieve leadership or at least closely follow the environment-related manufacturing technology leaders may lead to loss of market share. (As stated by John Logan before the US Senate Committee on Commerce, Science, and Transportation, Oct. 28, 1999, ‘Being second to market with innovation is not the way to maintain industrial leadership. That is not a situation in which we should want to place our key industrial sectors.’)

4 Use issues

The usage stage of the vehicle life cycle has large environmental impacts in terms of both resource consumption and the creation of wastes. It consumes 84% of the energy and produces 94% of the CO, 90% of the NOx, 62% of the SOx, and 91% of the non-methane hydrocarbon emissions [7]. There are a number of excellent on-line references to the environmental activities underway related to the usage stage of automobiles. These include the websites of the automakers [19–23] and other organizations [24–26].

Automakers based in the US, Japan, and Europe are each involved in activities directed at improving the fuel efficiency of their vehicles. In the US, under the aegis of USCAR, the Partnership for a New Generation of Vehicles (PNGV) had as one of its goals the production of a 3 L/100 km (80 mpg) vehicle that met the Tier II Clean Air Act Amendments gaseous emission standards and applicable ultra-low emission particulate standards. PNGV concept vehicles (utilizing compression-ignition direct-injection (CIDI) diesel engines) have recently been introduced according to the PNGV schedule by GM (Precept), Ford (Prodigy), and DaimlerChrysler (ESX3). Production models are scheduled to appear in 2004. In Europe, efforts are also underway to develop high mileage vehicles. For example, DaimlerChrysler recently unveiled a ‘3 liter vehicle’, also a diesel, that uses 3.4 liters of fuel per 100 kilometers (68 mpg) and that produces CO₂ emissions of less than 90 grams per kilometer. Toyota has produced the Prius hybrid vehicle that offers fuel economy near 3.9 L/100 km (60 mpg) and emissions low enough to qualify the car as a Super Ultra Low Emissions Vehicle (SULEV). Honda’s Insight hybrid also meets California’s Ultra-Low Emission Vehicle Standard and has a fuel efficiency of approximately 3.6 L/100 km (65 mpg). The other automakers will also soon be introducing hybrids. Table 2 summarizes the differences between the various low emission vehicle types.

One of the principal challenges associated with achieving high mileage vehicles is to meet simultaneously the relevant emission standards. The US (and more specifically, the State of California) has some of the world’s most stringent air
quality standards. EPA’s Tier II tailpipe standards (when converted into SI units) require nitrogen oxide emissions less than 0.044 g/km and particulate matter (PM) emissions less than 0.006 g/km for all classes of passenger vehicles beginning in 2004 (Figure 5 illustrates the Tier II requirements relative to the Tier I standards). This includes all light-duty trucks, as well as the largest SUVs. Vehicles weighing less than 2730 kg will be phased-in to this standard between 2004 and 2007. For the heaviest light-duty trucks, a three-step approach to reducing emissions will be followed to achieve compliance by 2009 [24].

According to Zorpette [27], the Tier II standards may present a problem for vehicles of the future, because the ULEV emission rates may be impossible to meet in a supercar that meets the other desired attributes. For a hybrid-electric car to even approach a fuel-efficiency of 2.9 L/100 km (80 mpg) would most likely require the use of a diesel engine, which produces more particle emissions than a traditional spark-combustion engine. A traditional spark-combustion engine, on the other hand, might satisfy particulate emission goals but would be unlikely to meet both the fuel-efficiency and the low-NOx requirements.

Kubota has adopted a strategy of developing/building engines that meets the world’s tightest emission regulations (rather than having different engines for different markets). According to the Kubota personnel, an audit of a group of

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Averaged over 80,500 km</th>
<th>Averaged over 161,000 km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NMOG1</td>
<td>CO</td>
</tr>
<tr>
<td>LEV: Low Emission Vehicle</td>
<td>0.047</td>
<td>2.11</td>
</tr>
<tr>
<td>ULEV: Ultra Low Emission Vehicle</td>
<td>0.025</td>
<td>1.06</td>
</tr>
<tr>
<td>SULEV: Super Ultra Low Emission Vehicle</td>
<td>A category of vehicle with emissions less than ULEV.</td>
<td></td>
</tr>
<tr>
<td>ZEV: Zero Emissions Vehicle</td>
<td>A category of vehicle defined that has no tailpipe emissions.</td>
<td></td>
</tr>
</tbody>
</table>

At present, applies only to electric vehicles.

1 NMOG: non-methane organic gases.

![Figure 5](image.png)  
**Figure 5** Tier I and Tier II US EPA air quality standards in SI unit
engines indicated compliance with Tier I requirements and emissions just within the Tier II standards. However, at present, existing manufacturing/assembly processes are likely to produce a number of engines not capable of meeting design intent. Quality improvement activities are therefore needed to continue to improve the precision of their manufacturing/assembly processes.

A number of research activities and initiatives are underway that are directed at reducing the environmental impact resulting from automobile use. These initiatives include the reduction of vehicle weight, development of alternative fuels, and development of alternative power sources. The issue of vehicle weight reduction has been discussed previously in the context of material selection. A variety of alternative-fuels for vehicles is being investigated: compressed natural gas, methanol, ethanol (unlike methanol, ethanol is non-poisonous and non-corrosive), diesel, etc. Research into cleaner burning diesel fuels may enable the development of a hybrid vehicle that achieves the emission and fuel economy goals associated with the PNGV initiative. MacLean and Lave [28] have studied the environmental implications of alternative-fueled automobiles in regard to air quality and greenhouse gas trade-offs. They concluded that compressed natural gas vehicles have the best exhaust emission performance while direct injected diesels had the worst. However, greenhouse gases can be reduced with direct injected diesels and direct injected compressed natural gas relative to a conventional fueled automobile.

Of course, much research is underway on the development of alternative power sources (engines) for automobiles. Figure 6 shows estimated fuel economies for a variety of these power sources. This includes work on CIDI (Compression-Ignition Direct-Injection) diesel engines, electric or battery power, hybrid vehicles (engine and battery power), and fuel cell technology. The challenges and advantages of diesels have been addressed previously, and certainly, diesel technology does not eliminate dependence on carbon-based fuels. Electric vehicles are currently being produced.

![Figure 6](image)

*Figure 6* Tier I and Tier II US EPA air quality standards in SI units

AdvSi: advanced spark ignition [29].
Except for ‘current’ configuration chassis/body is PNGV-class.
but at present, high cost and marginal performance limits their broad consumer acceptance. Battery technology is a limiting factor, and unless a breakthrough is achieved, electric vehicles seem to represent a transition technology. Hybrid vehicles counter some of the performance concerns of purely electric vehicles; however, cost is still a concern. Hybrids appear to be an effective near-term answer to transportation needs, but it seems unlikely that a vehicle with two power sources is an efficient long-term solution.

Hydrogen as a fuel source seems to be the most promising long-term solution. It is envisioned that fuel cell technology can then be employed to combine hydrogen with oxygen to create energy and produce water vapor as waste. The energy is then used to power a traction motor that drives the wheels. On-board storage of uncompressed hydrogen gas occupies about 3000 times more space than gasoline under ambient conditions and must therefore be pressurized and liquefied, or stored as a slurry or solid (e.g., metal hydride and carbon adsorption). On-board storage of hydrogen or a hydrogen-impregnated carrier may be initially met with resistance by consumers and significant infrastructure changes will be required (transportation via pipelines, H$_2$ stations, etc.). The required hydrogen can also be extracted (or reformed) from a conventional fuel (e.g., gasoline). This appears to be an effective transitional approach, especially in light of the challenges associated with accomplishing the required infrastructure changes for on-board hydrogen storage. The long-term role of on-board reforming is unlikely since it does produce emissions and does not eliminate reliance on carbon-based fuels. On-board storage of hydrogen presents a number of significant technical challenges including embrittlement and leak issues. Then, there is the issue of where the energy comes from to generate the hydrogen (from water). The use of carbon-based fuels is not the preferred solution to this problem – cleaner solutions are solar/wind power (i.e., renewable energy sources). However, it may be that only nuclear power can produce hydrogen in sufficient quantities for use as an automotive fuel.

As has been stated previously, this study was primarily concerned about the environmental issues surrounding manufacturing processes/systems. A brief overview of some of the environmental issues surrounding the automotive product has been provided, but this discussion only begins to address this complex issue. The next ten to 20 years will likely see a number of technology changes, both planned and unanticipated, and a wide range of vehicle and fuel types. The broad acceptance of any of these products is very dependent on the ability of the automakers to produce it cost-effectively. Thus, the economic success associated with these vehicles of the future is dependent on the manufacturing processes/systems of the future.

5 Post-use issues

The automobile is one of the most highly recycled consumer products. About 95% of retired cars enter the recycling system, and approximately 75% of each car in the system is recycled [30]. In spite of these seemingly large rates, the post-use stage of the vehicle life cycle still generates a significant amount of solid waste in the US (roughly 300 kg/vehicle) [7]. When a car is viewed as no longer having any useful life, it is transferred to a dismantler. The dismantler removes components that may be resold
for their material content (e.g., battery and catalytic converter) or as spare parts (body panels, wheels/tires, alternators, etc.). The remaining vehicle then passes to a shredding facility where large machines (shredders) cut the hulk into small pieces (6–10 cm in size). The pieces are then sorted into three streams: ferrous metals, non-ferrous metals, and automotive shredder residue (ASR). The sorted metals are sold to scrap metal dealers who serve as suppliers to primary metal processors (for example, steel mills). In other countries, the energy content of ASR is recovered through incineration. In the US, the ASR (largely metal and fluid contaminated polymers) is generally landfilled. However, with landfills closing on the East Coast of the US incineration is becoming more common. In the US a high proportion of vehicles are recycled because market-based incentives exist that promote the activity: virtually every material transfer involves some cash flow.

Graedel and Allenby [10] make several key points with respect to the automobile recycling system that exists today. Simply because a product is physically capable of being recycled, does not mean the technology and economics will support recycling. The automobile recycling system can be derailed at any step if the technology or costs are unfavorable. For example, prior to the wide use of vehicle shredding in the 1960s metal recovery from vehicles was difficult. In the 1970s as steel makers switched from open hearth to basic oxygen furnaces the amount of scrap steel that could be accommodated was significantly lowered, again hampering recycling efforts. These ‘lessons learned’ should be kept in mind as legislative initiatives, new materials, new vehicle concepts, etc. are contemplated. It must also be remembered that the decisions made today may not see their real impact for decades, i.e., the lifetime of a car.

It appears that the end-of-life handling of vehicles, such as described above, may soon change. Motivated by the diminishing availability of land-fill space in Europe and Japan (and for that matter in large US metropolitan areas), take-back regulations are being established that mandate vehicle return at the end-of-life and call for higher recovery rates for automobile recycling. Generalizing, it appears that by about 2005 an 85% recycling recovery rate and by 2015 a 95% rate will be required. These rates both include a small percentage of energy recovery associated with the incineration/pyrolysis of ASR. As might be expected, automakers are concerned about these targets and the take-back requirement. As challenging as these percentages appear, they will be even more challenging in the future as the ferrous metal content in the vehicle is reduced in favor of lighter metals and plastics to achieve higher fuel efficiencies.

Recent take-back legislation includes: i) A European Union Directive calling for the re-use and recycling (recovery) of end-of-life vehicles and their components, with a view to reducing waste disposal. No later than January 2006, the re-use and recycling of end-of-life vehicles shall be increased to a minimum of 80%. No later than January 2015, the re-use and recycling shall be increased to a minimum of 85%; ii) In October 1996, Japan’s Ministry of International Trade and Industry proposed a recycling target of 85% by 2002, and a target of 95% by 2015; and iii) In November 1998, the government of Belgium’s Flanders region introduced a take-back obligation that requires the last owner to hand in end-of-life vehicles to licensed recovery centers (or to car dealers if they buy a new car). Disposing of a vehicle in this way carries no charge. By 2005, 85% of each vehicle is to be recovered (up to 5% energy recovery allowed), and by 2015 the recovery rate must reach 95% (up to 10% energy recovery).
Given the need to increase recycling rates from their current level of about 75%, a principal challenge is to attack the remaining 25% that is associated with ASR. Altschuller [31] provides an excellent discussion of the challenges associated with addressing the ASR associated with vehicle end-of-life. There are three principal strategies for enhancing the amount of the vehicle that is recycled or re-used:

- Expanded application of ASR pyrolysis and incineration,
- Heightened use of ASR or ASR derived materials in products,
- Increased utility of vehicle dismantling and component re-use approaches.

Of course, it is unclear what effect any of these three strategies (or even the regulations being established in Europe and Japan) will have on the stability of the present vehicle-recycling infrastructure. Moreover, if the present recycling infrastructure is displaced with a more dismantling-oriented system, little thought has been given to the transition between the two systems.

One approach for dealing with ASR is pyrolysis. By heating the largely organic materials that constitute ASR in the absence of oxygen, it is possible to generate low-grade petrochemicals, along with ash and heat. If the petrochemicals produced from pyrolysis are unable to serve as feedstock for manufacturing processes, then incineration is a better alternative for the recovery of ASR energy content. While pyrolysis is technologically feasible, its implementation is inhibited by the present economics of automobile recycling. The potential profit from the sale of the petrochemicals (pyro-gas and pyro-oil) does not offset the combined costs of acquiring the technology and procuring the ASR feedstock. The principal advantage of both pyrolysis and incineration appears to be in keeping material out of landfills rather than profit. The economics of both are dependent upon the process efficiencies and whether the ASR feedstock must be purchased. Both pyrolysis and incineration are potential pollution sources, although new technology appears to control airborne emissions fairly well. In fact, one German website reports that a modern waste incineration plant has less emission than the trucks delivering the waste input. The issue of hazardous waste also represents an issue of concern (e.g., dioxins and chlorine).

Certainly, seeking another use for the materials within the ASR is preferable to incineration. Much research has been performed and will continue on this issue. US researchers at Argonne National Laboratory have developed an ASR separation technique that separates the ASR into three categories: polyurethane foam (15–20% of ASR by weight), particulate iron ‘fines’ (30–40%), and plastics (about 50%). Materials in the first two categories have market value. The foam can be used again (e.g., carpet padding or automotive applications). The iron fines are contaminated with other light metals, but can be used as feedstock for other products. Research is still needed to address the plastics-dominated balance of the ASR [31]. Toyota [32] has established an ASR recovery plant that can process 100 tons of ASR per day and is able to increase the vehicle recovery rate to 87%. The processes used in the plant are performed dry, and markets for the streams emanating from the facility have been established (bricks, sound absorption materials, etc.). The facility operates as a subsidiary to Toyota.

The two approaches (incineration/pyrolysis and separation) that are focused on the processing of ASR essentially seek to work within the existing vehicle recycling infrastructure. This infrastructure relies heavily on shredding processes and is
focused on material recovery rather than the recovery of individual components. Some researchers envision that it will require a sea change in the vehicle recycling system to achieve the high recycling rates referred to earlier. This view calls for the dismantling of vehicles, reuse of components where possible, and the recycling of the remaining materials. This comprehensive dismantling process differs substantially from the process being undertaken at present. As has been stated previously, currently only those components that can be readily removed and easily marketed are addressed. A comprehensive vehicle dismantling process involves taking the car apart piece by piece: fluids, engine, body, interior, etc. This more thorough dismantling/disassembly process would greatly reduce the amount of material that is shredded and therefore reduce the quantity of ASR. In part, enabled by higher levels of unemployment, nascent dismantling activities are underway in Europe (including those by US-based automakers), but more research is needed in this area. Attention must also be devoted to designing automobiles that are compatible with such dismantling activities. In the US, one company, Comprehensive Automotive Reclamation Services (CARS) of Maryland, is engaged in the total dismantling concept using technology from the Netherlands [33]. The Netherlands is a leader in state-of-the-art dismantling systems because their National Environmental Policy Plan finances environmentally sound automobile recycling [34].

Robert M. Day of the World Resources Institute [35] notes that ‘proactive companies take a leadership position that allows them some influence over the form of future constraints. A good example is BMW’s leadership on the issue of product take-back in Germany. By taking a visible leadership position on the issue, BMW anticipated, and even promoted, new regulatory take-back requirements which, because it held a strong market position in automobile disassembly, not only helped reduce waste but also provided it with a market advantage.’

An overview of the challenges associated with vehicle end-of-life has been provided. Motivated by their limited landfill space, regulations have been established in Europe that call for very high vehicle recycling rates. Similar regulations are being established in Japan. Given the existing recycling infrastructure, ASR incineration and pyrolysis (to recover energy content) are the easiest techniques to reduce the amount of material going to landfills. Other strategies seek to recover the original materials from the ASR (Argonne method). Europe is pioneering the use of vehicle dismantling techniques that could dramatically change the vehicle-recycling infrastructure. Take-back regulations do not exist in the US and given the relative abundance of landfill space, there is little economic incentive domestically to address the ASR problem. However, automakers based in the US must abide with the regulations of Europe and Japan for the vehicles that are sold there. As a consequence, they are closely following the developments overseas.

6 System-level issues

Previous sections have addressed environmental issues for various stages of the vehicle life cycle: materials, manufacturing, use, and post-use. There are several topics related to the automotive industry that cannot be accommodated as part of this classification scheme. These subjects include inter-company relationship
challenges, industry-government concerns, standards, the role of e-commerce, and philosophical changes in how a company views its business. A brief discussion of several of these issues is provided below.

The future of transportation (including the effects of such topics as e-commerce) is addressed by Graedel and Allenby [10]. They conclude that cultural trends will not greatly impact the short-term increase in the size of the automobile sector and the impact of e-commerce will not reduce the size of the automobile sector nor reduce the number of miles traveled by society. The number of automobiles will increase in the future. Research is needed on a variety of topics to support this growth in an environmentally sound manner. These topics include the development of new energy sources, more efficient energy storage systems, and advanced materials. In addition, research is needed that is directed at the development and maintenance of the complete transportation system to reduce its energy intensity and rate of resource consumption.

One of the disturbing trends that surfaced during the course of the site visits conducted during this study concerned a significant difference between the US companies and those in Europe and Japan. Individuals from US-based plants frequently commented that existing regulations tend to inhibit technology changes that could result in positive environmental effects. It seems that once a given process technology has been formally approved, as new (better) technologies are developed the burden to pursue the formal approval of these new technologies is often so large that the technology changes are not pursued. This appears to be in sharp contrast to industry-government interactions elsewhere in the world where there is a common vision regarding technological innovations directed at environmental improvement and economic development.

All of the automakers and suppliers that were visited, as well as those identified via the internet and the technical literature, are pursuing or have achieved some level of ISO 14000 certification. While the European-based organizations appear to view this pursuit as completely consonant with their overall environmental strategy, attitudes in Japan and the US seem to be more focused on certification as a hurdle to achieve market entry. Automakers in the US, Japan, and Europe all have well documented environmental strategies. In the US the Tier 1 suppliers are literate with regard to environmental issues and are at varying stages in the certification process. The expectation is that this ISO certification requirement will be passed down through the supply chain.

The management and synthesis of information across the automotive supply chain is an issue that extends well beyond the topic of environmentally benign manufacturing. There are a number of open issues about how to propagate environmental measures across the supply chain. For example, as the automakers track their energy usage from year-to-year, how can the energy usage of the suppliers be properly incorporated? Supplier data on emissions, wastes, and resource consumption is also needed, and techniques for combining all this information are needed. It is clear that much work will be required before some of the ISO 14000 standards will be met (e.g., ISO 14020 series on eco-labelling).

Several of the automakers were queried about corporate trends in selling ‘product use’ rather than the product itself. Under such a scenario, the manufacturer (or their agent) would retain ownership of the product and consumers would pay to use the
product. While they were aware of this concept, there does not appear to be any concerted effort to move the industry in that direction. On the other hand, the auto industry does distribute approximately 30% of its vehicles through lease programs, and one could argue that this is in fact ‘selling use’. There did not appear to be any significant differences in attitudes to this idea across the sites that were visited.

Building upon the thought of the previous paragraph, the notion of product stewardship, extended producer responsibility, and vehicle take-back represent considerable challenges to the auto industry. This is especially true in light of the trend in the US for automakers to delegate more and more of their manufacturing tasks to their suppliers. It is unclear who will be responsible for end-of-life vehicles. Certainly, communication with suppliers indicated that most do not believe they have any extended responsibility for a product after it has been sold to their customer. Given the previous comments about the post-use stage of the vehicle’s life cycle, it is likely that these issues will first be addressed in Europe.

In closing this section, one of the principal differences that was evident between the US and Japan/Europe was the attitude of consumers toward vehicles. While consumers in the US have recently complained about the high cost of gasoline, the prices are still well below the prices elsewhere in the world. The high cost of driving and maintaining a vehicle in Europe/Japan has, in part, created consumer habits/attitudes that differ remarkably from those practiced by individuals in the US. It is hard to imagine wide consumer acceptance in Japan/Europe of SUVs that are presently so popular in the US. A large gap exists between the environmental awareness of consumers in the US and those in Europe and Japan. Clearly, efforts must be undertaken to better educate the US public on matters related to the environment and resource conservation.

7 Summary

The automotive industry is one of the largest and most important industries in the world. As part of a global Environmentally Benign Manufacturing (EBM) benchmarking study, sites were visited in Japan, Europe, and the US. The following general observations about the emphases each country places on the environment are described below:

- In Japan the focus is on reduction of solid waste and energy usage/CO₂ emissions.
- In Europe attention is directed at reducing solid waste and achieving ISO 14000 certification.
- In the US emphasis is directed at compliance with government regulations and promoting worker safety.

In terms of public recognition of environmental issues, Europe appears to be the leader closely followed by Japan, with the US being a distant third. European governments are rapidly establishing a number of environment-related regulations, and Japanese industry closely tracks activities in Europe. Company-to-company differences in terms of the environment are far less than those from country-to-country.

Environmental issues surround each stage of the vehicle life cycle (materials, manufacturing, use, and post-use) and there are a number of system oriented issues...
as well. Research on the following topics is needed to address challenges associated with each life cycle stage:

- **Materials**: development of technologies to support the use of lightweight materials,
- **Manufacturing**: reduced waste and improved energy efficiency of processes including casting, sheet metal working, glass manufacturing, painting/coating/plating, machining, joining, plastics processing, and part washing,
- **Use**: advancement in alternative fuel/engine/power plant technology to achieve higher fuel economies and lower emissions,
- **Post-use**: improved recovery rates of ASR and increased attention to disassembly/dismantling, assessment of the economics/stability of the vehicle end-of-life system,
- **System**: role of suppliers and the management of information in the supply chain, and product stewardship.

It would also seem prudent to re-examine company/government interactions and the role of regulations in promoting environmental improvements. Do the existing relationships and regulations simply require compliance or do they promote never-ending improvement? Lastly, and perhaps most importantly, the US public lags far behind other nations in environmental awareness – strategies should be undertaken to close this gap.

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A global perspective on the environmental challenges


