Material Selection Processes in the Automotive Industry

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Prepared for the
Automotive Plastics Recycling Project

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Preface

The Office for the Study of Automotive Transportation (OSAT), in cooperation with researchers from other units of the University of Michigan, is undertaking a multiyear program of research titled "Effective Resource Management and the Automobile of the Future." The first project focused on recycling automotive plastics and provides an independent evaluation and review of the issues and challenges that recycling pose for this class of materials.

The Automotive Recycling Project benefited from the financial support of numerous sponsors: The American Plastics Council; The Geon Company; Hoechst Celanese; Miles, Inc.; OSAT's Affiliate Program; Owens-Corning Fiberglas; and The University's Office of the Vice President for Research. In addition, representatives of each of the Big Three automakers graciously served on the Project's advisory board, as did Suzanne M. Cole.

The project reports provide an overview and analysis of the resource conservation problems and opportunities involved in the use of plastics, and describes the factors that are likely to influence the future of automotive plastics. We develop information on the economic, infrastructure, and policy aspects of these issues, identifying the barriers to and facilitators of automotive plastics use that is less constrained by resource conservation and recycling concerns. At the same time, the Vehicle Recycling Partnership, a precompetitive joint research activity of the Big Three, is devoting its resources to the technical issues raised by recycling automotive plastics.

The Recycling Automotive Plastics project yielded six reports:

Life Cycle Assessment: Issues for the Automotive Plastics Industry (UMTRI Report #90-40-1), by Brett C. Smith and Michael S. Flynn, an overview of the LCA approach and its implications for automotive plastics (15 pages). This paper includes, as an appendix, the EPA design manual by Greg Keoleian and Dan Menerey, *Life Cycle Design Manual: Environmental Requirements and the Product System;*

Economic Issues in the Reuse of Automotive Plastics (UMTRI Report #90-40-2), by Daniel Kaplan, a general consideration of the economic barriers and issues posed by recycling automotive plastics (42 pages);

Recycling the Automobile: A Legislative and Regulatory Preview (UMTRI Report #90-40-3), by Suzanne M. Cole, Chair, Society of Plastic Engineers, International Recycling Division, describes the likely developments on the federal regulatory and legislative front that will influence the future of automotive plastics use and disposition (26 pages);

Postconsumer Disposition of the Automobile (UMTRI Report #90-40-4), by T. David Gillespie, Daniel Kaplan, and Michael S. Flynn, a review of the issues and challenges over the different disposal stages posed by postconsumer automotive plastics (54 pages);

Material Selection Processes in the Automotive Industry (UMTRI Report #90-40-5), by David J. Andrea and Wesley R. Brown, an overview of the factors and issues in vehicle manufacturers' material selection decisions (34 pages);

Automotive Plastics Chain: Some Issues and Challenges (UMTRI Report #90-40-6), by Michael S. Flynn and Brett C. Smith, a report of the OSAT survey of the automotive plastics industry (27 pages), plus appendix on types of automotive plastics.

These reports are all available from:

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Michael S. Flynn and Brett C. Smith

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The Recycling Automotive Plastics project provides an overview and analysis of the resource conservation problems and opportunities involved in the automotive use of plastics and composites, and describes the factors that are likely to influence their future. The project produced a series of six reports targeted to different aspects of the recycling challenges posed by automotive plastics. Combined with the technically oriented reports of the Vehicle Recycling Partnership, these reports should serve two purposes. First, they can serve as a broad introduction to the diverse and numerous dimensions of the recycling challenge for automotive managers whose areas of responsibility only indirectly or peripherally touch on recycling. Second, they can provide specialists with a broad panoply of contextual information, anchoring their detailed knowledge within the broad framework of recycling issues.

Automotive plastics posses numerous advantages for the automotive manufacturer and consumer. They contribute to lower vehicle weight, important for fuel conservation and emission reduction, while permitting the additional weight of new safety equipment. Plastics and composites are corrosion resistant, so their use can prolong vehicle life, and they are an important element in the paints used to protect other materials. They offer the designer greater flexibility, reducing the constraints that other materials often impose on shapes and packaging. If the difficulties of recycling automotive plastics present a potential barrier to their use, their advantages suggest that the barrier should be overcome, rather than deterring their continued automotive applications.

However, automotive plastics are visible and easily tied to the vehicle manufacturers. Hence, they may become targets for public opinion and government action out of proportion to their real role in solid waste disposal issues and potential for economic recycling.

I. The first report (Life Cycle Assessment: Issues for the Automotive Plastics Industry, UMTRI Report #90-40-1, by Brett C. Smith and Michael S. Flynn) provides an overview of the developing Life Cycle Assessment (LCA) approach and its implications for automotive plastics. An element of the emerging "design for the environment" method, LCA calls for an inventory, impact assessment, and improvement analysis targeted to the environmental consequences of a product across its production, use, and retirement. While environmental costs are typically unavailable, LCA supports the inclusion and consideration of any such costs that can be estimated, particularly for some of the environmental factors often ignored in traditional product decisions.

A fully developed LCA for vehicles or even components presents numerous significant analytic challenges to the industry, and may never become practical. First, a full LCA would be extremely costly, and the human and financial resources it would consume may be simply unavailable. Second, the handling of the data in an LCA can critically determine its outcome. The data for factors in an LCA are often lacking, typically measured in different metrics, subject to variable weightings, and frequently aggregated in different, noncomparable ways. Third, LCAs are difficult to evaluate and compare because they often reflect differing assumptions, varying boundaries, and there are no commonly accepted standards for their execution. Finally, the comparison of environmental costs with more traditional cost factors is at best difficult and speculative.

Nevertheless, LCA offers industry a sensitizing tool, useful for ensuring consideration of some environmental effects, and consistent with an industrial ecology approach to resource conservation. Moreover, the LCA approach resonates with some other developments in the automotive industry. Thus the industry is moving to more system-based material decisions, while its accounting system is evolving to a form that would more readily provide input for an LCA. The growing emphasis on cost reduction and waste elimination is also philosophically consistent with LCA goals. The industry has gained experience in other analytic techniques, such as quality function deployment, that have value even if only partially executed.

The automotive industry must shift from a reactive to a proactive approach in the management of its environmental effects. The ability to move quickly and surely to develop environmentally acceptable products and processes will be critical to future success. Establishing environmental credibility will increasingly afford the manufacturers an opportunity to create a positive image and thus a competitive edge in the marketplace. LCA might become an important tool in the development of an environmentally friendly product. However, cost pressures in today's competitive environment will likely make the industry approach environmental issues in a cautious manner.

II. The second report (Economic Issues in the Reuse of Automotive Plastics, UMTRI Report #90-40-2, by Daniel Kaplan) presents a general consideration of the economic barriers and issues posed by recycling automotive plastics. The United States currently recycles roughly 75% of the automobile, although plastics constitute roughly one-third by weight of the landfilled residue. An important question facing the automotive plastics industry is whether a combination of economic and technical developments might occur that would permit plastics to repeat the recycling success story of automotive steel.

Recycling automotive plastics faces two major economic barriers. First, the labor cost to recover the materials in usable form is quite high, making it unlikely that recycled stock can compete with the price of virgin stock. The second is that recyclers cannot rely on a consistent and stable flow of plastic scrap, as retired automobiles vary greatly in the level and type of plastic content. This makes it difficult, if not impossible, to establish end markets. Other economic barriers to successful recycling include the costs of transportation and recovery.

There are nonrecycling options for automotive plastics disposal. The landfill option still exists, although current trends suggest that it may soon become expensive enough to promote the use of other options, such as pyrolisis. Incineration permits energy recovery, but faces some of the same undesirable side-effects as landfills.

Pressure for recycling may raise the likelihood of policy interventions, as the government tries to avert the negative consequences of automotive plastics content, such as landfilling, while preserving its benefits, such as reduced fuel consumption and vehicle emissions. Government efforts will likely focus on attempts to capture the environmental externalities in the price of materials. However, recycling may have an economic down side: at least some automotive plastics, if fully recycled, could damage the viability of both recyclers and resin producers by creating an oversupply of material.

The numerous policy tools that might be invoked by government have a predictably wide range of consequences, and these must be incorporated into a cost-benefit analysis before appropriate selections can be implemented. In any case, the industry must be prepared to respond to a wide range of possible policy developments that will shape the economic viability of recycling.

III. The third report (Recycling the Automobile: A Legislative and Regulatory Preview, UMTRI Report #90-40-3, by Suzanne M. Cole) describes the likely developments on the federal regulatory and legislative front that will influence the future of automotive plastics use and disposition. Public policy often tries to incorporate social and environmental costs in the price of goods so that markets can achieve efficient use of energy and resources. The U.S. government has typically relied on regulatory actions to achieve this aim, but may now be moving more in the direction of market-based incentives. Moreover, many key legislators are persuaded that the model of extended producer responsibility, popular in Europe, offers a mechanism for encouraging producers to heed environmental costs in the design of their products. Legislation requiring producers to "take back" their products at the end of the life cycle make them ultimately responsible for its final disposition.

The new administration appears to be committed to a course of emphasizing environmental goals within a framework that permits rational trade-offs with the need for economic growth and development. Increased government R&D spending, much of it in cooperation with private industry, provides a foundation for the search for technical solutions to environmental problems. The Clean Car program is a major example of how this approach may affect the automotive industry.

EPA appears to lack the anti-business rhetoric that many feared, and is shifting to more of a pollution prevention approach rather than a pollution clean-up response. In addition, the director now has a credible staff in place. In spite of the fears of many, Nafta is unlikely to have major adverse environmental consequences for the United States, and may actually improve Mexico's capability to enforce its fairly stringent regulatory regime.

The give and take of politics will certainly determine exactly how the balance of environmental and economic considerations will be achieved in numerous specific decisions, from take back through recycled content legislation to the permit processes governing both new and old facilities.

IV. The fourth report (Postconsumer Disposition of the Automobile, UMTRI Report #90-40-4, by T. David Gillespie, Daniel Kaplan, and Michael S. Flynn) reviews the issues and challenges that postconsumer automotive plastics pose over the different disposal stages. The United States currently has an economically viable vehicle recycling industry, composed of dismantlers, shredders, and resin producers. Increased automotive plastics content and requirements for its recycling present enormous challenges to this industry. Developing appropriate markets for recycled stock is a critical challenge. Mandated, rather than market-led, recycling could threaten the very existence of this recycling industry and doom recycling efforts.

Shrinking landfill capacity and rising prices threaten the recycling industry, which must dispose of superfluous material. Increased nonrecyclable plastic content threatens profits, as it often replaces material that can be sold and increases the volume of residual material for landfilling. For plastics to be profitable, the labor costs associated with recovery must be lowered and/or the price of recovered materials rise. Development of automated sorting, chemical and physical technologies for reduction, and pyrolisis all offer some hope, but the public opinion environment and automotive industry demands may force the pace of recycling beyond the infrastructure's capacity.

There are steps the industry can take to facilitate higher recycling rates for automotive plastics. First, plastic components and parts can be designed for easy disassembly and dismantling. Second, plastics can be clearly and consistently labeled, to avoid contamination in the recycle stock. Third, designers can try to limit the numbers and types of incompatible plastics in the vehicle and within any part or component. Fourth, further development of incineration and energy recycling could well support resource conservation, and ultimately higher reuse of nonplastic automotive materials. Fifth, techniques for recycling commingled plastics merit support.

V. The fifth paper (Material Selection Processes in the Automotive Industry, UMTRI Report #90-40-5), by David J. Andrea and Wesley R. Brown) discusses the factors and issues in vehicle manufacturers' material selection decisions. Material selection in the automobile industry is an artful balance between market, societal, and corporate demands, and is made during a complex and lengthy product development process.

Actual selection of a particular material for a specific application is primarily driven by the trade-off between the material's cost (purchase price and processing costs) and its performance attributes (such as strength and durability, surface finish properties, and flexibility.) This paper describes some thirty criteria used in material selection today. How critical any one attribute is depends upon the desired performance objective. The interrelationships among objectives, such as fuel economy, recyclability, and economics, are sufficiently tight that the materials engineer must always simultaneously balance different needs, and try to optimize decisions at the level of the entire system.

The vehicle manufacturers' materials engineer and component-release engineer play the pivotal role in screening, developing, validating, and promoting new materials, although initial consideration of possible material changes may be sparked by numerous players. These selection decisions are made within a material selection process that will continue to evolve. This evolution will largely reflect changes in the vehicle and component development processes to make them more responsive—in terms of accuracy, time, and cost—to market and regulatory demands. The balancing of market, societal, and corporate demands will continue to determine specific automotive material usage in the future.

VI. The sixth paper (Automotive Plastics Chain: Some Issues and Challenges, UMTRI Report #90-40-6), by Michael S. Flynn and Brett C. Smith) is a report of the OSAT survey of the automotive plastics industry (vehicle manufacturers, molders, and resin producers). This survey collected the industry's views on recycling, often contrasted with more general automotive industry views reflected in our Delphi series. This report covers four general topics: recycling and disposition challenges; regulatory challenges and responses; recycling in material selection decisions; and the future of automotive plastics.

The industry in general views a variety of economic, technical, and infrastructural recycling concerns as more important in the case of plastics than of metals. The automotive plastics industry, while perhaps viewing these concerns somewhat differently, sees a complex set of recycling challenges, varying over both the automotive plastics production chain and the stages of recycling/disposition. The manufacturers see these challenges as more severe than do molders or resin producers, and the industry generally views market development and disassembly as more critical stages. The automotive plastics industry generally favors more emphasis on open-loop recycling and the development of the disassembly infrastructure, while evidencing little support for disposal in landfills.

Government CAFE regulations are important drivers for automotive plastics use. However, government is also moderately committed to recycling. The various levels of government are somewhat likely to establish differing regulations to encourage recycling, but are less likely to impose outright bans on any current plastics/composites. Among the range of governmental incentives for recycling, tax incentives are generally seen as useful, but more restrictive and limited actions are seen as not particularly useful. The automakers are unlikely to restrict the total amount of plastics in the vehicle, although they will probably limit the use of unrecyclable plastics and restrict the number of types of plastics in the vehicle. They are also likely to pass through any recycling requirements to their suppliers, the molders and resin producers.

The recyclability of automotive plastics is not yet a major factor in automotive materials-selection decisions, ranking far below the traditional factors. Recyclability is viewed as, at most, of moderate importance to the customer and the industry. Moreover, there are concerns about the cost of recycling automotive plastics, and very real apprehension that there is little market for them, once recycled. These considerations are likely to drive up the cost of plastics, should they be recycled, and thus further discourage their use.

Our results present a somewhat mixed picture as to the future role of automotive plastics in the North American industry, although in general a promising one. There are clear drivers for their use, including their advantages for design flexibility, and these are likely to be buttressed by more stringent fuel-economy regulations in the future. However, there are concerns about their ultimate disposition when the vehicle is retired. These concerns reflect a different environmental priority, one that the automotive industry does not yet view as a customer demand, nor as a "heavyweight" materials-selection factor.

Our survey suggests that the automotive plastics industry and its vehicle producing customers are aware of and concerned about the environmental challenges that lie ahead. Moreover, they are seeking solutions to these challenges that are environmentally sound and responsive to the demands of vehicle purchasers and users. To be sure, their views are often influenced by their own position in the plastics value chain, and they reveal some tendency to prefer solutions that impose responsibility on other stages in that chain. However, they reject solutions that might relieve their own burden, but are environmentally problematic, such as landfilling.

These papers suggest that the automotive industry's adoption of plastics and composites is moving forward. The pace of adoption is responsible, and the industry treats the environmental effects of its material decisions neither lightly, nor as someone else's problem. However, that pace is cautious, reflecting many uncertainties. These include concerns that the industry may be disproportionately blamed by the public for problems in recycling disposed materials, and apprehensions that the industry may be disproportionately targeted by government to resolve such problems. Since plastics and composites confer a wide variety of benefits, including environmental advantages, the industry may be erring on the side of too much, rather than too little, caution.

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INTRODUCTION

The market acceptance of a vehicle is a function of many variables, including

> ...the sales price, technical and aesthetic qualities of the product, the efficiency of the sales network, the image created by advertising from before the first advertisement to the market launch and the first sales and on and on in various forms throughout the whole market liFe of the product, the reliability of the car, servicing and spare parts, and the terms of the warranty offered to the customer.[1]

Material selection heavily influences each of these vehicle success factors except perhaps for the sales network efficiency, and even that may change as environmental demands develop. This paper explores the material decision process so that manufacturers, component suppliers, and material providers may better understand the interlocking web of compromises that shape the pursuit of value-added alternatives and the avoidance of unprofitable compromises.

The authors assume that the reader is reasonably versed in the issues facing today's automotive industry. Cost reduction, quality improvement, regulatory compliance, and so forth are well recognized industry competitive issues. Difficulty arises in the creation and execution of action plans to address these issues in an environment of rapid and multifaceted change, limited financial and human capital, and time pressure. Tomorrow's automobile will provide better performance, function, and comfort, while emitting lower emissions, consuming fewer gallons of gasoline, resulting in fewer human injuries, and requiring fewer dollars to build and purchase. The only solution to these seemingly conflicting objectives is to take a systems view of the product and industry. However, systems discipline is not yet standard operating procedure for the domestic auto manufacturers and, thus, for their supply base.

A company must understand the material selection process to pursue a true, systems, product-development approach. Optimization across vehicle performance, price, fuel economy, emissions, and safety have not occurred consistently.

> Aluminum and other lightweight materials have often been used to assist in the creation of small weight decreases, which can change vehicle weight

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[1] Sergio Pininfarina, "Design and Competitiveness," *Automotive Technology International 1989* (1988), 19-24.

> classes for US Environmental Protection Agency fuel economy calculations. While this practice has sometimes been tactically effective for the car maker, and will probably continue, it prevents the consideration of a systems approach that can result in truly significant weight changes, more attractive cost trade-offs, and strategic advantages.[2]

An illustration of the material optimization challenge is shown below (figure 1). This figure shows the tradeoffs and compromises among vehicle and component performance, material and component cost, and manufacturing necessary to achieve the best overall value. "With respect to these three points an equilibrium condition has to be reached when choosing a certain material for the best technical behavior with the greatest economical profit[3]." Any other point within the triangle indicates the overvalued position of a particular attribute. "Consequently for the best material selection one has to pay attention to all three of [these values] to the same degree, which means practically that the design engineer has to think not only of the material properties with respect to the part behavior but should never forget the qualification of the material for the production and manufacturing steps.[4]"

To understand the total, material-decision-making process one must look at all the phases in the life of a vehicle: design, product engineering, tooling construction, production processes, surface finishing, assembly, market impact, and recycling of used scrap.[5] We first explore the basic vehicle product-development process because material decisions are made within this overall context. Next, we expand this perspective by discussing the material-decision-making process from the point of view of product-development. We then consider a range of factors, including material performance versus material cost, component manufacturing and vehicle assembly cost, regulatory compliance, product volume, design, customer demands, competitive responses, and recyclability to illustrate the complexity of the material selection process. With this as a base, we finally catalog current material use for the reader's reference.

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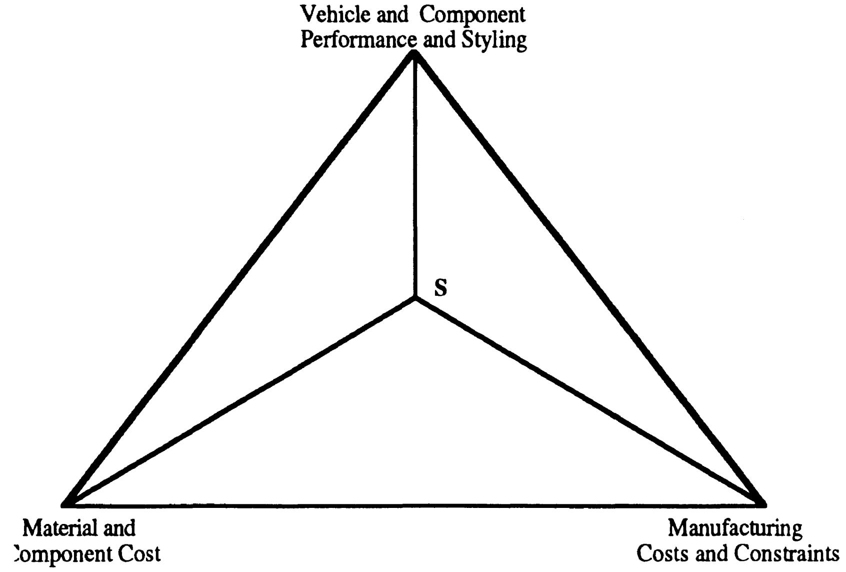
[2] Maurice McClure and Ronald Sharp, "The Practicality of Aluminum for Automotive Body Structure," *Automotive Technology International 1992* (1991), 77-81.

[3] Claus Razim, "The Potential of New Materials for Automotive Engineering," in XXII FISITA Congress, vol. 1 (Dearborn, MI and Washington, D. C.: Society of Automotive Engineers), 224-230.

[4] Ibid.

[5] F. Forcucci, "Towards PMCAs for Bodywork Parts," *Automotive Technology International 1989* (1989), 77-80.



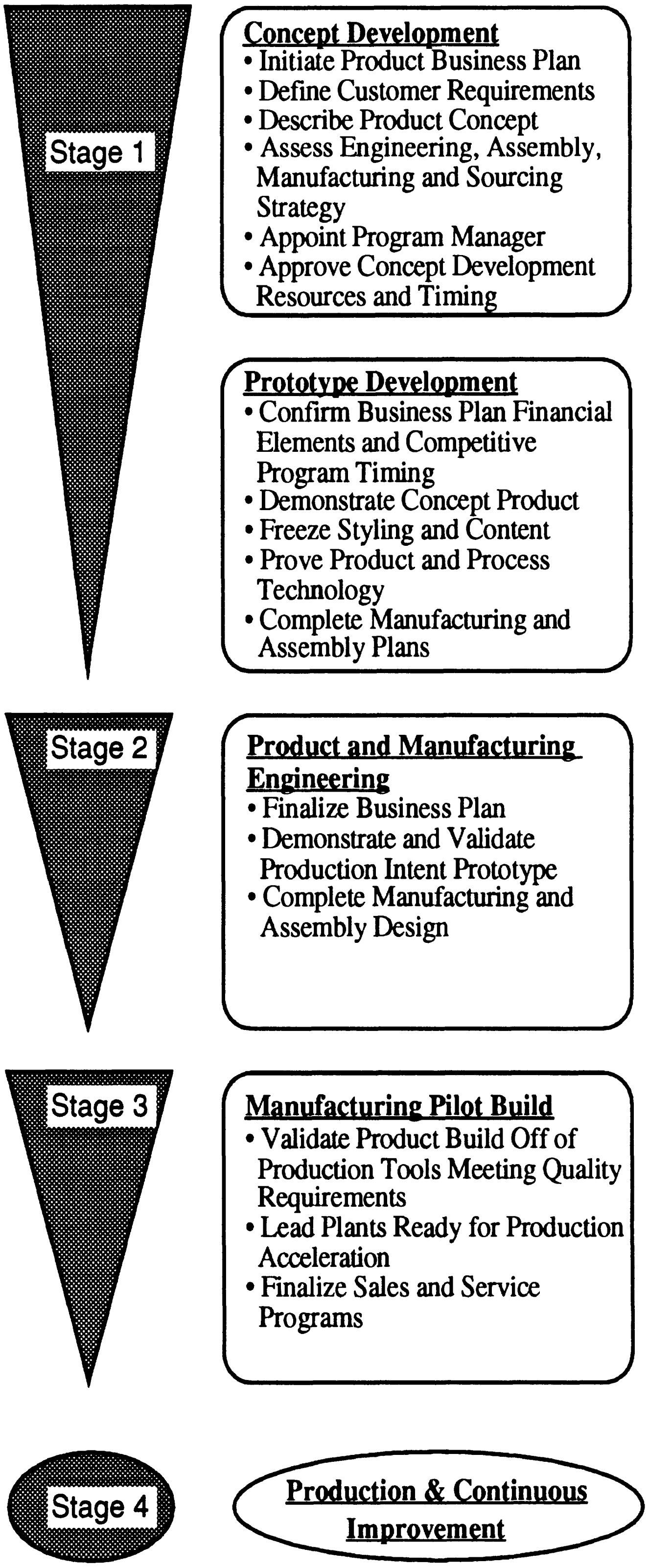
Source: Adapted from Claus Razim, "The Potential of New Materials for Automotive Engineering"

Figure 1 Material Selection Decision Making

THE VEHICLE PRODUCT DEVELOPMENT PROCESS

The product-development process shown in figure 2 is used, in varying forms, by the Big Three. Stage one incorporates the product concept, market research to determine current and future customer demands, and the review and selection of all the design and engineering alternatives. Before exiting stage one, materials for the product have been selected and costs finalized. Stage two follows with the final prototype approval as well as tooling processes. Stage three incorporates the construction of the tools, validation of the tooling capacity, and the preparation of the facilities for the product. In stage four, the final vehicle is produced; yet there is a continual review of the vehicle itself, the manufacturing and the engineering processes, and the product's component and system reliability. The continuous improvement comes from the feedback of the company and its workers, the customers, and the market. Furthermore, this continuous improvement is important so that when the company returns to stage one for another product, any mistakes and delays it may have encountered can now be avoided.

A number of factors over the last decade or so have led to today's product-development process. One of the major reasons is that there have always been problems in the decision-making process during the development of a vehicle. New processes are designed to remove such problems. There have been many examples of teams for product-development programs. These teams have consisted of people from all parts of the company who would normally be in on the process only at specific phases of development, but now are placed together from the beginning.



Concept Development
- Initiate Product Business Plan
- Define Customer Requirements
- Describe Product Concept
- Assess Engineering, Assembly, Manufacturing and Sourcing Strategy
- Appoint Program Manager
- Approve Concept Development Resources and Timing

Prototype Development
- Confirm Business Plan Financial Elements and Competitive Program Timing
- Demonstrate Concept Product
- Freeze Styling and Content
- Prove Product and Process Technology
- Complete Manufacturing and Assembly Plans

Product and Manufacturing Engineering
- Finalize Business Plan
- Demonstrate and Validate Production Intent Prototype
- Complete Manufacturing and Assembly Design

Manufacturing Pilot Build
- Validate Product Build Off of Production Tools Meeting Quality Requirements
- Lead Plants Ready for Production Acceleration
- Finalize Sales and Service Programs

Production & Continuous Improvement

Figure 2A Typical American Vehicle Development Process

Product-development teams receive guidelines from a corporate committee on the design theme, return on investment, and other consumer market targets, but the actual development of the vehicle is left to the team. As a team they work out the actual styling, performance characteristics, component specifications, and other details that comprise a total vehicle. The functions represented on these teams include product planning, quality control, marketing, finance, design, engineering, manufacturing, parts and service, and procurement and supply. Consequently, decisions are made cross-functionally, with all factors of product-development accounted for in the process, and with a total awareness of all the tradeoffs that must be made when developing a vehicle.

A major problem with the old product-development process was its lack of flexibility. The process flow today allows much more flexibility right from stage one, enabling the company to revamp its designs, components, manufacturing, and engineering processes to meet changing market conditions. Customer satisfaction has become the top priority in company goals and strategies. Flexibility, combined with the team concept, allows people in the product-development process to focus on what the customer wants. With the marketing people involved from stage one, all the relevant, customer-profile information is shared with all functions, thus creating a team that understands its product's market, and, best of all, understands the intended customer.

Another aspect of the team method is the inclusion of the finance function. Because the finance staff is present at beginning, the staff becomes more knowledgeable about the development process, and they develop a vested interest the project's success. Meanwhile, the product and manufacturing engineers are finally able to understand why concessions need to be made, and how financial decisions are analyzed in the development process.

Finally, this product-development process has numerous checkpoints along the development course to promote and maximize the team's productivity. These checkpoints allow the team to focus on areas that pose critical time constraints, thus cutting down on overall development time, and to focus more on the "critical path" of events determining the length of the project.

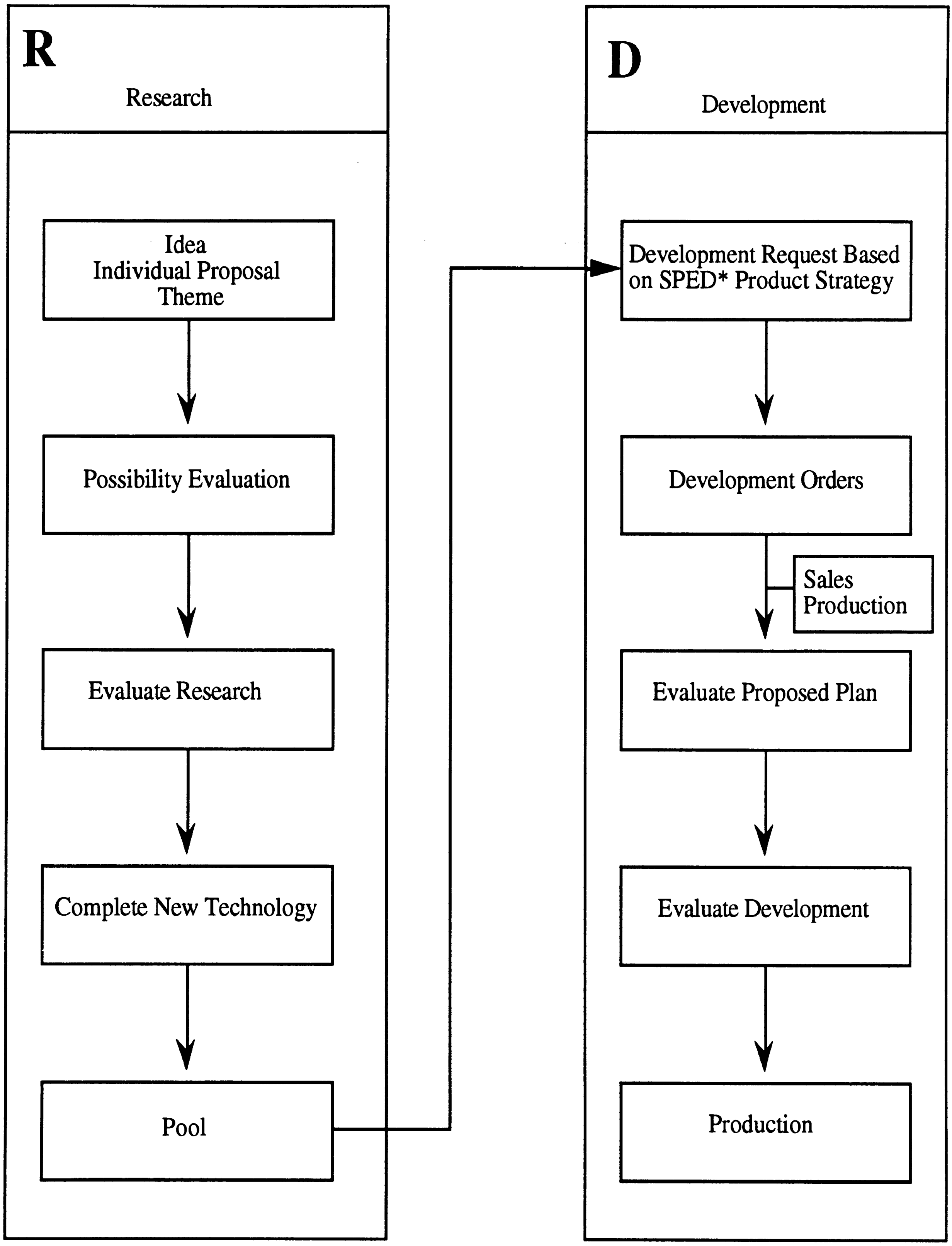
There have been a few examples over the last decade of successful team development programs. First, in "Team Taurus," Ford Motor Company experienced the benefits of people working together from the start and developing the product concurrently. The team would ask itself, throughout the development process, “Would I buy this car?” In addition to those functions listed above, "Team Taurus" also included dealers, consumers, insurance companies, and even some academic ergonomic experts. These groups were encouraged to write up wish lists for the new vehicle, yielding responses such as “easier to service” (dealers), “lower maintenance costs” (consumers), and “engineering to ease assembly” (line workers). Furthermore, suppliers were brought in early to make sure final component designs were compatible with the manufacturing processes.

Second, in Chrysler’s “Team LH” experience, the team acted as a small business, since, all the major disciplines of a company were present in the team. With 70 percent of the Concord, Vision, and Intrepid content sourced outside of Chrysler, suppliers were made integral members of the team, and given much more responsibility in the design and development processes. Suppliers helped create components hand-in-hand with Chrysler people, sharing in the design and financial information.

The Japanese approach to vehicle development follows a somewhat different path, although the processes have many commonalties. Figure 3 illustrates the Japanese approach to product-development. The Japanese system emphasizes the development of technologies that are proven and held in a reserve pool for future programs. This process divides research, or advanced engineering, from development, or current engineering. This reflects the Japanese manufacturers heavier dependence upon its supply base. With more independent research, conflicts between manufacturer and supplier over control of engineering, purchasing, and other issues should be minimized if the manufacturer respects the intellectual rights and economic commitments of the companies that contribute to the idea pool.

Another difference is the amount of overlap among the stages. The Japanese tend to be more integrated, which allows faster development, increased flexibility, sharing of information, cooperation, and the ability to delay decision making to the last possible moment. For the Japanese, their development process promotes cross functional more than the American process. The Japanese are encouraged to interact with outside information sources and to acquire diversified knowledge and skills. This provides the ability to solve a wide array of problems.

There are several commonalties between the typical American and Japanese systems. First, both processes have top management acting as a catalyst, providing a strategic direction or goal for the company, yet leaving room for those in charge of the development project. Second, the teams are given much autonomy and act as their own company. For the Japanese, this allows the team to avoid the rigidity and day-to-day hierarchy of the company.



*Sales, production, and engineering development

Figure 3 A Typical Japanese Vehicle Development Process

THE MATERIAL-DECISION-MAKING PROCESS

Figure 4 presents a flowchart of the automotive material-decision-making process. Two major factors govern the timing and review process of material changes. First, a material change for a current engineering update will carry less product timing risk than a material change for a new platform in the product-development process. Second, a material that has already been approved by a vehicle manufacturer carries fewer change risks than new materials for applications. Each of these conditions carry varying degrees of timing, cost, and performance risks for the materials engineer and the component release engineer.

The vehicle manufacturers follow a variety of different, specific material-decision-making processes. We have attempted to generalize the process, timing, and decision-making points. By presenting this outline, suppliers may formulate targeted marketing strategies based on specific customers and products.

Entry Points and Motivations Material change investigations and requests may originate from the responsible material or component release engineer, the component manufacturer, the assembly plant, or purchasing. While these persons or groups have shared objectives, each has their own particular reasons for initiating a material change. The assembly plant (point A in figure 2) may initiate a material change based on assembly quality difficulties or paint and other processing difficulties. Typically, process engineers will contact either the component manufacturer or the component release engineer with these problems.

The component manufacturer (point B) may be driven by piece-cost-reduction efforts or changes in tooling to reduce fixed capital costs. Typically, the suppliers work with the material providers and release engineers to resolve these problems. Additional issues for the component manufacturer include workplace health, productivity (cycle time), and yield. Each of these concerns may be cause to initiate an investigation for a new material.

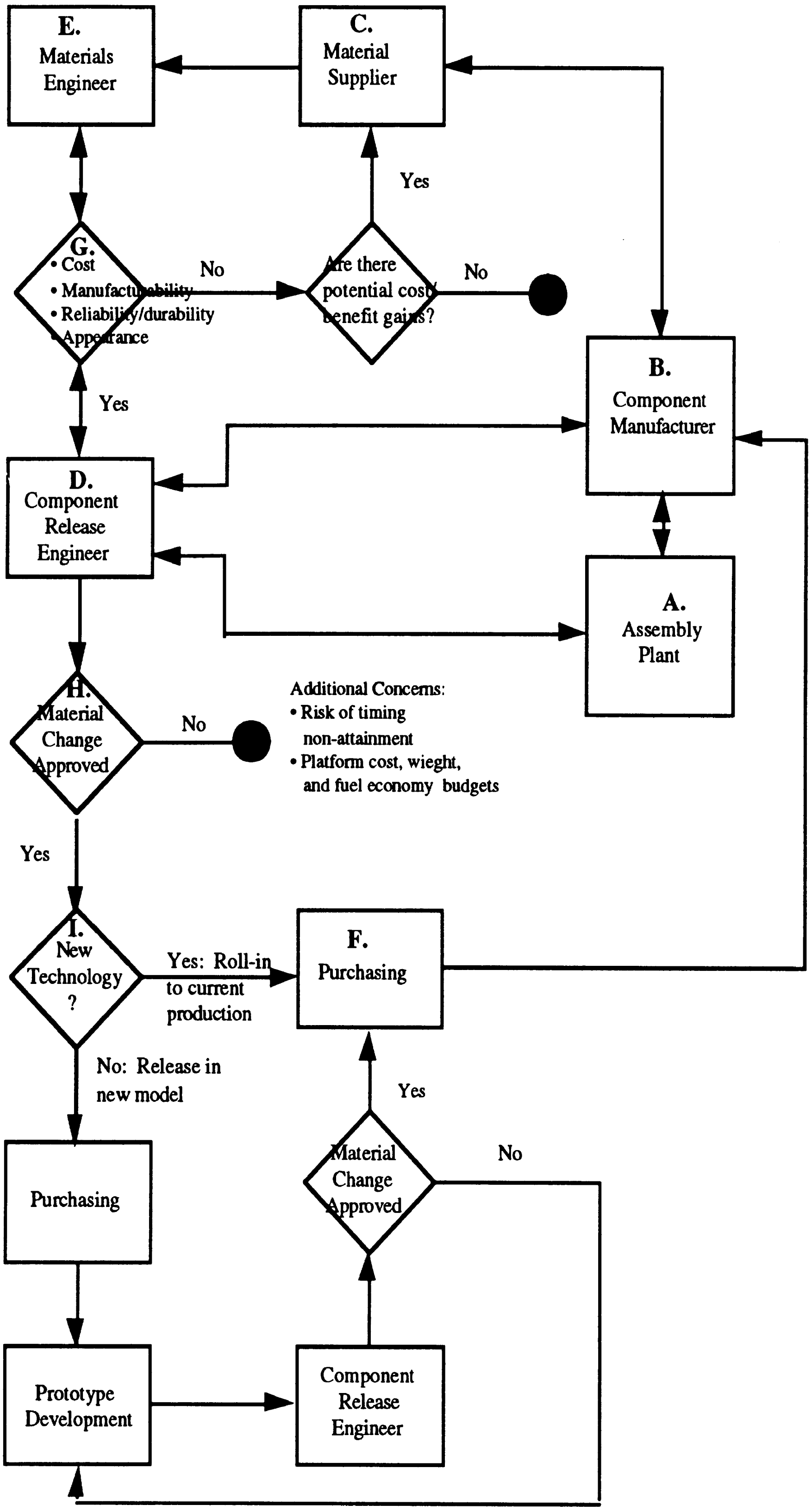


Figure 4 The Materials Decision Making Process

The material supplier (point C) may try to promote the introduction of a new material with higher performance characteristics—and potentially higher profit margins. Having a material approved for a new application may open up new markets for a supplier and increase production capacity utilization. The component manufacturer and materials engineer typically receive the initial information on new material applications. Component release engineers (point D), as members of a vehicle or component system development team, are primarily driven by their cost and weight budgets, physical performance demands, and processability. They work with materials engineers, material suppliers, component manufacturers, and assembly plants to meet these budgets.

The materials engineer (point E), as a focal point of materials development, is responsible for and motivated by each of the above factors. Purchasing's role is primarily to work with the release engineer and quality function to assure the selection of a supplier who can meet the blueprint specifications. Purchasing (point F) may actually initiate a materials-validation review if it selects a new supplier for an existing part number and that supplier uses a nonconforming process. If a component manufacturing process changes, than the materials engineer and components release engineer must approve the change. Purchasing typically changes suppliers for reasons of cost, quality (all forms including delivery, etc.), and capacity utilization.

Decision Making Points The materials engineer and component-release engineer are the two key decision-making points. The materials engineer screens new material proposals against manufacturability, reliability, durability, and appearance objectives. The component-release engineer is responsible to a platform team requiring pilot and production parts availability at a given time and cost. These engineering groups within the vehicle manufacturers are typically conservative. They prefer to maintain the known rather than venture into the unknown. This is not a negative reflection on the individuals, but rather an observation of the system in which they operate. Failure to perform to time, cost, and weight budgets may end a person's career. When given a choice, a material or a process with known levels of cost, reliability, performance, and delivery will sell better to material and component engineers.

The materials engineer judges new material proposals against established design guidelines and methods. For new materials or new applications of existing materials, for which there are no accepted design guidelines, the materials engineer is the critical decision-making point since he or she will establish the material-validation process. The validation criteria may create or eliminate an opportunity for a supplier. The validation process prescribes the physical properties (temperature resistance, mechanical strength, environmental resistance, and other such criteria) that a material must achieve or surpass (decision point G).

The materials engineer becomes an internal sales agent for any new application because he or she promotes the idea's consideration and application throughout the decision-making process. To sell a new material through the system, a materials engineer works with the material and component suppliers to create a plan that achieves the other stakeholders' objectives, including processability, cost, weight, and vehicle structural integrity issues. Two or three candidate materials might be chosen and separate test plans developed for each. The internal testing process occurs between the materials department and current engineering until one material is selected. The selected material will be recommended to the component release engineer who will incorporate the new specification into the component's blueprint.

The component-release engineer serves as a critical interface between the vehicle platform chief, project design engineers, vehicle assembly operations, purchasing, and the supply base. As such, he or she works with the materials engineer to assure that the validation process is met and that platform cost, weight, and fuel economy budgets are met, and that the program timing objectives are attained (decision point H). These budgets are business-decision constraints imposed on the component-release and materials engineers. While the engineering function may influence these constraints, material decisions are, for the most part, made in light of these parameters.

The component-release engineer is the one who "pays" for any increases in costs or delays in program timing. Therefore, a case must be made that vehicle cost and performance budgets will be met before a release engineer will release blueprints with a new material specification to purchasing. Because the release engineer operates at the interface of a variety of key decision makers, tradeoffs are possible. For example, an engineer from one system may take on additional costs if it can be proved that another system may reduce its costs—these tradeoffs are typically arranged at the vehicle platform level.

Because of these possible tradeoffs, a release engineer may request that multiple prototype parts be tested. When all the parts come together into one system, the resulting costs or weights may be better judged, and specific component objectives may be altered. At this time a single prototype part will emerge as the best contributor to the overall component system's performance optimization.

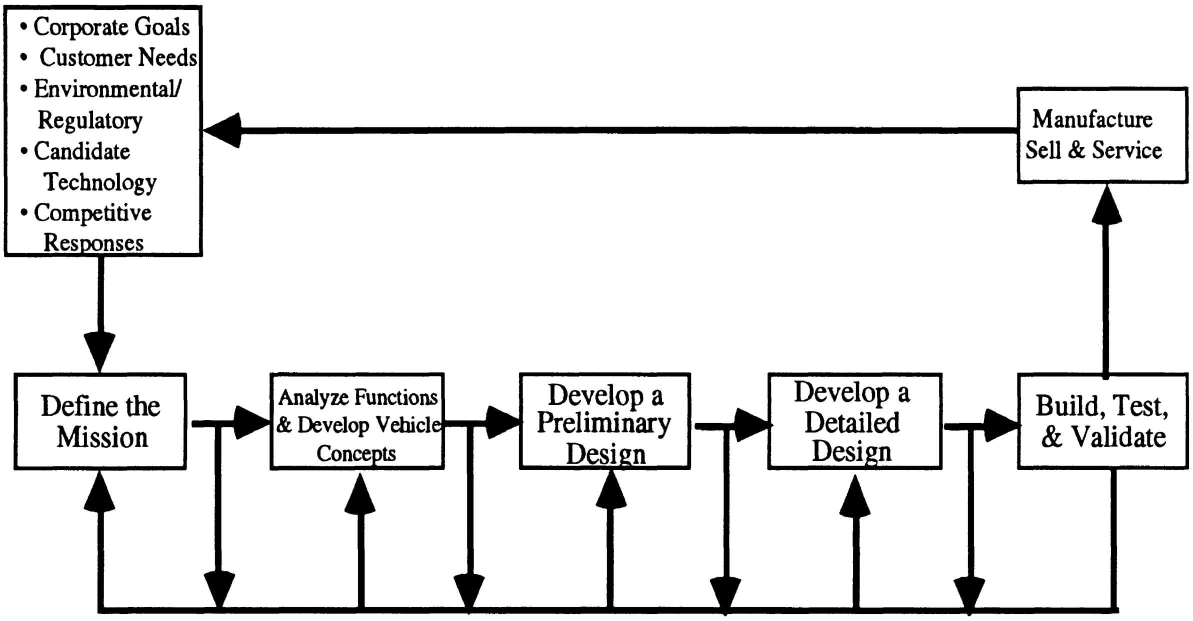
A new material application will typically take place on an existing platform as an engineering change (decision point I). By using an existing model as a platform for new material technology, a company reduces the possibility of delaying a new model launch due to unproved technology. Some companies have taken a strategy of using a lead vehicle to introduce new materials. These vehicles, with the latest materials and other features, are targeted to early adopters of new technology. This provides a halo affect around the product's and company's image and allows a company to test the waters with new technology in limited numbers, since these lead vehicles typically have smaller production runs. This allows a company to carefully track field problems and warranty claims, correcting any unforeseen problems without the risk of large recalls.

BUSINESS FACTORS AFFECTING MATERIALS DECISIONS

Introduction Many material attributes comprise the selection criteria. Additionally, the design, purchase, tooling, processing, assembly, postconsumer costs, and other factors are all costs associated with material selection. This section introduces the broad material attributes engineers require. Following sections address more specific considerations such as material performance, component manufacturing costs, regulatory compliance, and production-volumess.

The development of an automobile is an interactive process fulfilling broad corporate objectives and detailed design requirements (see figure 5). The application of systems approaches increasingly places greater emphasis on a simultaneous approach to developing vehicle concepts, preliminary and detailed designs, and testing and validating. Significant savings in engineering hours and expenses, improvements in manufacturing quality, and reductions in warranty expenses come through intense iterative activities across functions involved in downstream activities. These gains come from placing decision making at the lowest possible level—within the control of those with the best operating knowledge. Therefore, rather than a formal top-down approach, new product-development structures attempt to separate top management's market and financial objectives accountability from the platform team's engineering and manufacturing responsibilities.

Materials are at the core of every decision throughout the described product-development process. A literature search through material technical papers found thirty characteristics mentioned as materials selection criteria (see table 1). These characteristics alone and together influence material decision making within a variety of regulatory, business, and market constraints, including CAFE, emissions, and safety compliance (for example, strength and weight/density ratio); manufacturing (machining speeds); design (texture); marketing (dent-resistance); and others. Some of these attributes are similar in technical definition, but are used differently in the objective and subjective evaluation of specific applications. The priorities among criteria will vary given the type of vehicle, component application, production-volume, and so forth. These priorities depend upon the economics of the specific situation, target budgets, production scales of economies, and other factors. From these budgets, fixed costs (including profit) are subtracted, leaving the manufacturer or supplier a budget to consider possible design and process options. These priorities are highlighted as each material or component example is discussed in following sections.



Source: Schilke, Fruechte, Rillings, & Rohde, "A Systems Approach to the Future—Automotive Style," 1988 Fisita Conference.

Figure 5 The Vehicle Engineering Process

Table 1
Criteria used in Automotive Material Selection/Component Design

• Corrosion resistance	• Formability/drawing quality	• Recyclability
• Dent-resistance	• Hardenability	• Stiffness/Strength
• Development lead time	• Impact resistance	• Surface finish
• Dimension tolerance	• Machining speeds	• Tear strength
• Durability	• Moisture absorption	• Temperature resistance
• Economics	• Near net shape capability	• Texture
• Elasticity	• Noise, vibration, harshness	• Thermal expansion rate
• Fatigue resistance	• Part consolidation ability	• Tooling costs
• Flexibility	• Processing throughput	• Wear resistance
• Fracture resistance	• Processing time	• Weight/density

Material Performance/Cost Tradeoff The specific material performance characteristics described below are difficult to completely isolate from one another. Two examples illustrate this complexity. First, sheet molding compound (SMC) may be justified for a body panel on the basis of reducing weight, fuel consumption, tooling lead time, and part complexity; improving corrosion resistance, styling freedom, and dent and damage resistance; and controlling piece, tooling, and facilities costs.[6]Second, reaction injection molding (RIM) polyureas used for automotive exterior parts provide excellent mechanical performance, outstanding thermal properties, integrated processes, and excellent surface quality.[7]

This section highlights the many attributes inherent in a material type. These characteristics tend to provide the set of first level material discriminators. While dependent upon specific applications, in general, passing these criteria places a material on the decision maker's short list for consideration Other criteria may be weighted with cost to provide needed tie breakers—the final decision between two or more relatively equivalent materials.

Strength and Durability Material selection begins with consideration of the application and its physical durability requirements. Certainly historical precedence and product-specific attributes, like appearance, may weigh more heavily for particular applications. However, in these situations, design and other priorities may force cost penalties (in engineering hours, raw material purchases, and finished component price) to assure component durability. Strength and durability have many associated attributes and measurement methods including critical and stringent levels of elasticity, fatigue resistance, high-temperature creep and fracture resistance, corrosion resistance, and wear resistance.[8]

A materials engineer must consider tradeoffs, such as those displayed in table 2. For equal strength, as measured by bending strength, sheet steel, glass fiber reinforced plastic, and aluminum require significantly different thicknesses. Varying thicknesses result in different weights, which may assist or hinder a systems engineer attempting to meet weight and cost budgets.

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[6] Ken Rusch, "SMC: The Proper Choice for Exterior Body Panels," *Automotive Technology International 1992* (1991), 71-74.

[7] R.E. Camargo, D. A. Bityh, and T. A. Amato, "A New Generation of Materials," *Automotive Technology International 1990* (1989), 87-91.

[8] David J. Naylor, "The Future of Engineering Steels," *Advanced Materials Technology International 1990* (1989), 31-41.

As the below table shows, keeping only one variable constant (bending strength), it should be possible to reduce the weight of body components by 40 percent through the substitution of plastic for steel and 50 percent through the substitution of aluminum for steel. However, weight substitution tradeoffs are complicated. For example, to equal the crumpling behavior of steel, an aluminum component needs to be approximately double the thickness of steel which results in only 33 percent weight savings, not 50 percent. With varying alloys and heat treatment the medium crumpling strength for aluminum may be two to four times that of steel. Therefore structural analysis needs to consider these alternatives.[9]

Table 2
Alternative Material Characteristics
at an Equal Bending Strength

Material	Thickness (mm)	Density (g/cm^3)	Mass per Unit Area (kg/m^2)
Sheet Steel	0.9	7.8	7.02
Glass Fiber Reinforced Plastic	2.5	1.7	4.25
Aluminum	1.3	2.7	3.51

For most applications, steel offers structural integrity, optimized design, and ability to maintain dimensional geometry throughout the manufacturing process. Considering other performance criteria, engineering steels offer control of composition and hardenability, near net shape part production, and improved passenger safety through thoughtful design features. Steel's reputation for durability and reliability comes through the use of uniform and clean stock, and high-strength/low-alloy grades, along with general toughness, fatigue and wear resistance, and predictable properties.[10]

Specialized grades of steel, although expensive at point of purchase, offer attractive life-cycle benefits. For example, Chrysler and GM are using more stainless steel in exhaust systems because it is two to three times as durable as the aluminized steel it replaces. This durability improvement increases customer satisfaction and reduces warranty claims for exhaust components.

Strength and durability issues applying to systems dominated by plastic usage differ from those of steel. For example, a tradeoff between amine-extended polyurethane/urea and polyurea systems formulated to the same flexural modulus, all with internal mold release, show the

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[9] Peter Walzer, "Appraisal: Aluminum, Plastics, or Steel and Iron," *Automotive Technology International 1992* (1991), 64-68.

[10] Naylor, op. cit.

polyureas providing improved polymer toughness, tear strength, and thermal stability, with enhanced thermal properties of heat sag and moisture growth. There is also improved overall surface finish for the polyurea formulation. These advantages extend to the plant floor because polyureas have longer flow times. These longer flow times provide greater part and shot size capability. Advanced polyurea formulas also offer quality, productivity, and economic advantages over previous RIM materials.[11]

Plastic applications are becoming more demanding with requirements for stiffer structural systems such as those provided by the incorporation of fibrous fillers, most notably glass.[12] The design execution of the Chrysler LH dashboard is an example of these increased requirements. By designing plastic reinforcing members into the dashboard's understructure, Chrysler was able to reduce harmonic vibrations dramatically.

The real test of plastics rests in their acceptance for structural applications. The auto industry is trying to upgrade its fiber reinforced plastics (FRP) expertise by looking at the technology for specific structural components.[13] Industry research consortia are exploring the use of composite-intensive structures.

Surface Finish Material surface finish and the ability to take coatings and paints is an important consideration. Typically, materials may be grouped into two categories, exposed and non-exposed. Exposed materials, such as body panels, are styling sensitive. Exterior body panels require a Class A finish. A Class A finish is a function of the surface finish and surface treatment. Surface finish refers to specific characteristics such as formability and surface smoothness. Surface treatment involves paint and coating treatments. Other considerations such as surface finish and light reflectivity require a material to accept specified primer, base coat, and top coat coatings. Every material has advantages and disadvantages.

Exposed interior components demand texture and touch considerations as well. Materials present a variety of images including luxurious, sporty, and inexpensive. Beyond the visual, materials determine the sound and feel of a switch, the comfort of a seat, and the support of an arm rest. Each of these parts is individual in its design and material selection; however, they all come together to determine the personality of an automobile.

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[11] Mark E. Sanns and Frank Cekoric, "RIM Polyurea for Improved Fascia Productivity," *Automotive Technology International 1990* (1989), 61-65.
[12] Gordon F. Smith, op. cit.
[13] Ibid.

Typically, nonexposed parts, such as inner panels and other structural pieces, require less surface finish attention: aesthetics, customer perception, and maintenance are lesser issues. Parts in extreme operating temperature or corrosion areas often require special finishes because of the need for special coatings.

Corrosion Resistance A general target for surface-metal-corrosion resistance is 10 years or 100,000 miles. Increased panel-gauge thickness is one method of achieving this goal. However, this may not be the most cost effective method of resisting corrosion. Increasing gauge adds to vehicle weight, material costs, and associated capital expenditures. Body-panel-corrosion-penetration resistance is approaching nine years.[14] This improvement has come, even with gauge-reduction weight savings, through the increased use of galvanized steels, sealants, waxes, and innovative design. Coatings and sealants may be the most effective corrosion resistance method available.[15] Many Delphi VI (1991) material panelists believe that while body-surface-panel-corrosion resistance has basically been resolved, underbody structural components, underhood, and other components operating in extreme environments still present problems.

Aluminum and plastics offer inherent corrosion resistance. Aluminum is highly resistant to corrosion under most conditions. However, extreme long-term corrosion performance and spot welded and adhesive-bonded joints are situations requiring pre-treatment.[16] Galvanic corrosion is a concern when two different metals are brought together. Careful selection of fasteners and corrosion protection is required.

CASE STUDY:

> Aluminum Space Frame Structure Example This example suggests the basic thought processes and major considerations of a decision involving a material and manufacturing process change. It involves the consideration of substituting an aluminum extrusion space frame and panels for conventional steel. This example is not unreasonable; Ford, for example, has exhibited the Contour concept vehicle utilizing this construction method. It has also been rumored that Ford may produce an aluminum-intensive vehicle in the mid-1990s. Ford's Synthesis 2010 concept car utilizes aluminum for all major body panels and structural components. Based upon this concept car, Ford is testing a fleet of aluminum-intensive Taurus vehicles.

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[14] David E. Cole, David J. Andrea, and Richard L. Doyle, *Volume 3: Materials, Delphi VI Forecast and Analysis of the U. S. Automotive Industry through the year 2000,* (Ann Arbor, MI: University of Michigan, 1992).

[15] Coatings and sealants cause problems for recycling plastic components. See T. David Gillespie, Daniel Kaplan, and Michael S. Flynn, "Postconsumer Disposition of the Automobile," (University of Michigan Transportation Research Institute report no. 93-40-4, 1993).

[16] McClure, op. cit.

In this case study, the lineal sections (e.g., pillars and rocker panels) of a vehicle space frame are formed by extrusions that are bent into required shapes. Castings are used where shapes are complex and where extrusions are mated together. Aluminum sheet covers the space frame, and is used for floors, roofs, firewalls, and other panels.

The primary advantage of this manufacturing and assembly process is that it requires fewer parts, only half the number of parts required for a conventional-sheet-metal body. One-piece aluminum extrusions replace several individual stampings that would traditionally require welding or other forms of fastening. With fewer parts and joints, design and engineering hours for the initial program as well as subsequent model revisions are reduced.

Tooling costs are minimized in two ways. First, there are fewer die sets to procure. Second, extrusion dies are less expensive than a set of stamping dies at the outset. However, extrusion dies wear more quickly than stamping dies, making extrusion tooling more of a variable than fixed cost. In a three-year program, the estimated tooling break-even point (at which steel tooling cost per unit is less than the extrusion die set) is over 300,000 units. At 50,000 units, the extrusion tooling cost savings are approximately $125 per vehicle, dropping to approximately $75 per vehicle savings at 100,000 units.

There are also lower assembly costs because of fewer required labor operations, and the potential, reduced, physical space requirements, and lower energy usage. These savings reduce break-even points, allowing increased program specialization and profit margins.

Consumer satisfaction may also increase with an extruded aluminum space frame. The durability of the body should increase with fewer joints. Fewer joints also limit potential noise, rattle, and vibration problems. Minimizing weight potentially improves performance, handling, and fuel economy.

Table 3 shows the component cost breakdown of two exemplar parts. The structural body part costs $4.95 more in aluminum than in sheet steel, while the aluminum exterior sheet panel carries a $5.25 penalty. These component cost penalties must be balanced out at the platform level against other constraints. For example, a vehicle may be close to a CAFE weight classification, and Delphi VI panelists estimate a kilogram of weight saved is valued at $0.91. Therefore, a platform manager might accept the exterior sheet substitution at $1.91 per kilogram of weight saved—even at a component cost disadvantage.

Table 3

Material Price Comparisons for Stamped Steel and Aluminum Components

Primary Structural Body Part Example

Assumptions	
Steel purchase price, $/kg	$0.77
Aluminum purchase price, $/kg	2.86
Steel scrap value, $/kg	0.13
Aluminum scrap value, $/kg	1.32

	Steel Sheet Part	Aluminum Sheet Part
Part weight, kg	5.00	2.90
Kg saved		2.10
Percent weight saved		42.00%
Kg purchased	7.00	4.06
Purchase price, $	$5.39	11.61
Scrap credit	($0.26)	($1.53)
Total material cost	$5.13	$10.08
$ increase per part		$4.95
$/kg weight saved		$2.36

Exterior Sheet Body Part Example

Assumptions	
Steel purchase price, $/kg	$0.85
Aluminum purchase price, $/kg	$3.85
Steel scrap value, $/kg	$0.13
Aluminum scrap value, $/kg	$1.32

	Steel Sheet Part	Aluminum Sheet Part
Part weight, kg	5.00	2.25
Kg saved		2.75
Percent weight saved		55.00%
Kg purchased	7.00	3.15
Purchase price, $	$5.95	$12.13
Scrap credit	($0.26)	($1.19)
Total material cost	$5.69	$10.94
$ increase per part		$5.25
$/kg weight saved		$1.91

Source: Maurice Sharp and Ronald McClure, "The Practicality of Aluminum for Automotive Body Structure

Component Manufacturing and Vehicle Assembly Considerations Increasing capital-expenditure requirements on the cost side and competitive product-pricing pressures on the revenue side are both forcing manufacturers to reduce their costs by enhancing manufacturing productivity, shortening product-development cycles, improving management efficiency, and increasing product and service quality levels. Parts consolidation plays a major role in overall productivity increases. Creative design and material selection may reduce part counts that, in turn, limit product complexity, design and engineering effort, tooling costs, assembly time, and original-equipment and service-part inventories. According to Clark, innovative plastic design has been slow due to the individual limitations of the plastics processing techniques. "Integrating injection and compression molding through multiprocess technology is the technology of the future for large complex parts that replace several smaller parts and have exacting requirements."[17]

Clark proposes addressing material selection, as it applies to component manufacturing and vehicle assembly considerations, in a multiprocess fashion. Multiprocess technology is the analysis of all possible processes and materials that come together to produce a component, or on a broader scale, a complete system. This systems approach optimizes the benefits of each process and material to ensure that complex components achieve engineering intent and maximize consumer value. For all materials, a multiprocess analysis improves productivity and product performance through weight reduction, material utilization, manufacturability, and reliability.[18]

Engineering thermoplastics have played a major role in part consolidation, since they offer a wide performance range of blends and alloys. These raw-material benefits are complemented by ever expanding injection-molding-technology processing options. Vehicle manufacturers have found that material substitution for given discrete parts supports incremental cost reduction. However, parts consolidation results in major cost reductions when savings in engineering, assembly, tooling costs, streamlined manufacturing, and other associated benefits are added up.

Tooling Costs There are also differences in handling and fabrication of steel and aluminum sheet, which can affect component cost: stamping-die design issues, stamping-die

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[17] Christopher L. Clark, "The Impact of Multi-Process Technology," Automotive *Technology International 1991* (1990), 95-97.
[18] Ibid.

materials, stamping rates, lubrication/cleaning issues, handling equipment, handling and segregation of manufacturing scrap.[19]

Processing: Number and Ease of Operations Materials have a wide range of processing considerations that affect direct material and labor costs, quality, and productivity. For steels, in addition to a high absolute level of machinability, the consistency of free-cutting is important. This consistency enables production engineers and managers to plan and execute machine shop schedules profitability, as well as facilitate just-in-time manufacturing.[20] Plastics offer a whole set of specialized considerations. For example, Bayflex 120 polyurea system is an RIM material. When this system of materials was introduced in the late 1980s it offered increased thermal stability, reduced moisture absorption and growth, and better compatibility with internal mold release (IMR) agents. Bayflex 120 also offers longer flow times relative to conventional polyureas, thus allowing the production of larger parts.[21]

Changing materials involves changing processing operations. For example, GM introduced powder metal engine bearing caps on its 3.1 Liter V6 engines in 1993 and will add this material to the 3.8L V6 in 1994. This switch will reduce secondary machining operations and reduce vehicle weight as compared to cast iron.[22]

Costs may vary significantly for alternative processes within a given type of material and fabrication method. Relative to heat-treated steels, air-cooled forgings exhibit greater consistency of properties, no distortion from quenching, and comparable machinability (with equivalent strength). Therefore, cold forgings can directly pass from the forge to the machine shop without storage while awaiting heat treatment. This results in shorter track times, lower inventories, and reduced financial costs. To increase the use of cold forging, these advantages must overcome the perception of the process' low toughness. To improve toughness, small amounts of titanium are added for grain refinements. However, this additional cost of adding titanium may overcome the benefits described above.[23]

Near net shape production—a function of part design and tooling—is a growing trend, if not an absolute requirement. Production of components closer to their final required shape and tolerances reduces secondary machining operations. Application of near net shape strategies

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[19] McClure, op. cit.
[20] Naylor, op. cit.
[21] Sanns, op. cit.
[22] Stephen E. Plumb, "What's Ahead from A to Z?" *Ward's Auto World*, September 1992, 39.
[23] Naylor, op. cit.

require design, equipment, and tooling developments for specific materials and processes.[24] For example, warm forging (between 500-900°C) produces better material yield, surface finish, and tolerances than traditional hot forging. However, higher-strength steels can more easily be formed than cold forging, into complex shapes without expensive, secondary time- and energy-consuming annealing treatments.[25]

Process Cycle Time As with processing operations, each material and production-process cycle time has its own characteristic set of costs and benefits. Plastic-process cycle time is a function of cure rates, tool release rates, multicavity mold ability, and mold cleaning requirements.[26] For example, polypropylene composite materials and alloys (PCMA) provide an engineer with a class A quality surface finish, low coefficient of linear expansion, and extreme temperature stiffness and impact resistance. PCMAs also offer a competitive processing advantage over other thermoplastic materials. Because of PCMAs flow rate and other processing characteristics, it is possible to produce more than 1000 mudguards a day on one double-cavity mold using relatively small molding machines.[27] At this rate 62.5 mudguard sets can be processed per hour—or a little more than one set per minute. This processing capacity determines the number of molding machines and tooling sets required for a given production forecast.

Process Yield Process yield measures the amount of raw material and indirect material that is converted into the final product. Process yield and material scrap are a function of product design and material selection. Scrap may be material turnings, molding sprus, or rejected parts. Any scrap source must be minimized, and companies must make an effort to increase the in-plant recycling of scrap.

<u>CAFE and Environmental Regulation Compliance</u> The management of a vehicle manufacturer's corporate average fuel economy (CAFE) fleet average affects vehicle design, product and option offerings, product introduction timing, and marketing strategy. There is great uncertainty regarding future CAFE standards. Respondents to the University of Michigan's Delphi VI forecast expect CAFE standards to rise from the current 27.5 mpg to 30, 33, and 36 in

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[24] Ibid.
[25] Ibid.
[26] Sanns, op. cit.
[27] Forcucci, op. cit.

the years 1995, 2000, and 2005, respectively. It is interesting to note that the same respondents believe attainable fleet averages are approximately 1 to 2 mpg lower in each given year.[28]

A majority, 59 percent, of the respondents to a recent Ward's Auto World survey believe that lowering vehicle weight is a higher priority today than a year ago. However, 52 percent believe that the auto makers are not willing to pay a premium for lightweight materials. In fact, one respondent commented that "most [companies] are pushing the value-per-pound envelope now."[29] These changes have not radically redirected material strategies; in fact, 62 percent of the respondents report not knowing of any examples of significant material substitutions to improve fuel economy. Fuel economy improvements are currently being pursued through more efficient powertrains (54 percent), lightweight materials (29 percent), and downsizing (16 percent). By the year 2000 the focus will be on lightweight materials (51 percent) and more efficient powertrains (39 percent).[30] These results are very similar to the University of Michigan Delphi VI results.

However, vehicle manufacturers cannot independently reduce vehicle sizes and material weights to increase fuel economy—emissions and safety requirements, customer comfort, styling, and functional demands must also be achieved.

> . . . Greater demands will be made on safety and comfort and so a reduction in weight cannot be achieved simply by reducing the size of the car. Instead one must investigate whether a weight reduction can be realized through better utilization of the materials used, and to what extent greater use might be made of materials of lower density, such as aluminum and plastics.[31]

A platform manager must balance regulatory certification and market demand requirements. The body, with the greatest percentage of total vehicle weight, is a major target of weight reduction efforts. The weight of a typical, medium-sized car is divided approximately 33 percent to the body; 33 percent to the underbody, chassis, suspension, and braking functions; 20 percent to the powertrain; and 10 percent to all other categories, including electronics and fluids. All components are subject to material reviews, and weight reduction requirements are forcing increased use of aluminum crankcases, plastic intake manifolds, plastic water pumps, and even plastic toothed-belt wheels.[32]

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[28] Cole, David E., David J. Andrea, and Richard L. Doyle, *Volume 2: Technology, Delphi VI Forecast and Analysis of the U. S. Automotive Industry through the year 2000*, Ann Arbor, MI: University of Michigan, 1992.

[29] Cole, *Delphi VI, Volume 2: Technology.*

[30] *Ward's Auto World*, "1992 Ward's Auto World Materials Survey," September 1992, 47-48.

[31] Walzer, op. cit.

[32] Ibid.

Competition from aluminum and plastic put pressure on steel makers to develop improved alloys. Weight, durability, and flexibility requirements will drive the competition between the basic material groups. "That means medium-strength steels in the 30,000 psi to 50,000-psi (2,100 to 2,800 bar) yield range are gaining favor. These steels, available from all major steel companies, are more dent-resistant and lighter weight than conventional drawing-quality steel but much more formable than high-strength steels."[33]Medium-strength steel offers 10 percent weight savings over conventional steel at a 5 percent cost premium. High-strength steels, in turn, are two to three times as weight-efficient as medium-strength steels. Because of this cost/benefit ratio, Ford is utilizing large amounts of medium-strength steels and Chrysler LH doors are now medium-strength steels.[34]

A vehicle lightened by 250 kg (551 pounds) consumes 20,000 liters (5,280 gallons) less fuel in 160,000 km (99,360 miles). The same reduction in weight produces about 4,800 kg (10,582 pounds) less carbon dioxide in 160,000 km. Vehicle performance also increases with weight reductions—10 percent reduction in weight results in an 8 percent reduction in 0 to 100 km per hour (62 mph) acceleration time. Weight reduction also improves handling ability.

Weight Reduction Efforts Substituting aluminum for steel is a popular method of reducing body weight. An aluminum panel, even double the thickness of steel, weighs approximately a third less, and crumpling strength improves twofold to fourfold. Aluminum also requires less anticorrosion protection, which adds to its weight saving over steel. Although there are some specific requirements for effective stamping of aluminum parts, these differences add little to fabrication costs, as compared with the cost of steel. The lower weight allows increased performance and reduced engine sizes and other parts, both of which have beneficial cost implications.[35]

ICI Polyurethanes recently introduced RIMLine 8709, a new liquid polyurethane, for use as an automotive interior, trim-panel substrate. RIMLine 8709 is composed of isocyanate and polyol/additives. Current applications for RIMLine 8709 include the sun-shades on the Ford Explorer, Lincoln Continental, and two Chrysler models, as well as the 1992 Pontiac Bonneville interior trim panels. Use of RIMLine 8709 reduced the weight of each door by about 2 pounds. It is estimated that further applications on instrument panels, quarter and door panels, rear

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[33] Plumb, op. cit.
[34] Ibid.
[35] McClure, op. cit.

package shelves, seat backs, sunshades, and even headliners, can save as much as 50 percent of the substrate weight. This could reduce the weight of each passenger car 20 to 25 pounds.[36]

Ford UK is experimenting with a glass-fiber engine, utilizing aluminum cylinder liners and crankshaft bearings. The outside of the engine as well as the valve cover and oil sump are made of plastic. Using such alternative materials can reduce weight by about 30 percent versus a cast iron version, and about 10 percent versus an aluminum version. In addition to weight savings, noise is reduced by 3 decibels.

Economics and Production-Volume Forecasts Economic analysis plays a significant role in material selection and much of it is initially driven by a platform's production-volume forecast. Production-volume forecasts are a hotly debated topic, and suppliers often believe that the manufacturers are overly optimistic. Production-volume forecasts are determined through analysis and compromise among market research and analysis, fleet merchandising, production capacity allocation, and other related groups. This routine determines the broad base volumes that form the base for business and production planning. Bills of materials are broken out for each platform or model and, from this level of detail, requests for quotes are generated for the suppliers.

Inaccurate forecasting raises several important issues. First, breakeven points vary for particular materials. Materials requiring lower fixed investment in areas such as design and tooling "pay back" these investments at a lower cumulative volume than materials involving higher levels of investment. For example, tooling is less expensive for SMC than for steel, but steel becomes attractive at volumes between 100,000 and 150,000 and above. At this point, the more expensive steel tooling may be amortized over enough units to make piece costs attractive. Slower plastic cycle times force the need for additional molding lines and increased investment, thus reducing the initial lower tooling cost advantage. High volumes can only be achieved with steel stamping. Steel may be attractive at even lower production-volumess if strategies such as low-cost dies, high steel uniformity, and superior stamping-plant throughput are followed.

The second important aspect of accurate forecasting is determining actual supplier costs. Decisions on specific materials, tooling, manufacturing processes, and so forth are influenced by expected production-volume. For example, in 1989, General Motors Cadillac DeVille and Fleetwood models introduced the first high-volume application of a major thermoplastic exterior body panel. Targeted at approximately 150,000 units, the tooling costs for thermoplastic front

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[36] Nick Ghoussaini, "A New Plastic Product for Molding Interior Panel Substrates," *Automotive Technology International 1992* (1991), 309-310.

fender panels are only a fraction of the costs of sheet metal panels. In the case of the 1989 Cadillac program, the cost for hard tools for the fenders was $1.2 million, whereas Kapp estimates sheet metal tooling would have been twice that.[37] Auto capacity expansion is often built in a stair-step approach—economies of scale direct suppliers to expand in large stages, with knowledge that capacity will be filled by one or two suppliers. Accurate forecasting maximizes the supplier's ability to plan capacity expansion and design components.

Technological innovation may reduce the need of some materials, while increasing the demand for others. For example, as costs fall and perceived reliability increases, electrical multiplexing will reduce the need for wiring and connectors. On the other hand, if design is considered a technology, plastic demand has grown because of innovative, integrated design.

> Although plastic is light, it costs about three times as much as steel for each kilogram of material. Nevertheless, the use of plastic materials in cars has increased at a higher rate than aluminum because it enables the integral production of complex components, and there are the added advantages of resistance to chipping and minor impacts, anti-corrosion resistance, noise damping, heat insulation and, more important for interior equipment, pleasant tactile characteristics.[38]

The true cost of any component design or material selection involves a wide range of variables and considerations.[39] For example, aluminum components in cars are usually more costly than iron or steel, but one must look at the total system to make accurate estimates of the cost of manufacturing. Generally, a large portion of the cost premium for aluminum components is due to the higher cost of aluminum metal relative to comparable volumes of steel and iron. The ratio of aluminum costs to costs of iron, to fill the same volume, is about 2:1, and the ratio of the cost of aluminum sheet to the cost of an equal surface a thickness of steel sheet is a little less than 2:1. Aluminum has been used to assist in creating small weight reductions, which can help change vehicle weight classes for the EPA fuel-economy calculations.

However, this practice prevents the consideration of a systems approach that can result in significant weight changes and more attractive cost trade-offs. Aluminum offers product and process flexibility in creating components or systems for bodies and suspensions. In addition to sheet aluminum stampings, castings, extrusions, and forgings can be used to make aluminum body or suspension parts.[40] "Due to its density advantage (specific gravity of 2.7 versus 7.8), the price disparity between aluminum and steel is usually cut by at least half on a price per surface

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[37] James L. Kapp, "Thermoplastic Exterior Body Panels," *Automotive Technology International 1990* (1989), 61-65.

[38] Waltzer, op. cit.

[39] Brett C. Smith, "Life Cycle Analysis: Issues for the Automotive Plastics Industry," (University of Michigan Transportation Research Institute report no. 93-40-1, 1993).

[40] McClure, op. cit.

area basis and is further reduced when the value of stamping plant scrap is considered. Sheet aluminum scrap has about ten times the value of sheet steel scrap on a price per pound basis."[41]

Postconsumer Material Disposition Figure 6 presents the automotive life-cycle material flow. Automotive engineers are considering postmanufacturing and consumer flows for the following reasons. First, public and legislative environmental pressures are forcing the issue. Although automotive landfill contributions are small compared with contributions from other sources, the prominence of the automobile makes it a symbol for environmental efforts. Second, while the average growth per vehicle of plastic usage has slowed, the vehicles coming into the disposal stream are 10 to 15 years old, including the vehicle model years that experienced the greatest growth in plastic per unit. As the result of this and an increased number of vehicles entering the disposal stream, auto landfill residue has almost doubled since 1980.[42] Automotive landfill contributions will increase over the next decade.

Third, disposal economics are changing. Landfill costs are rising and disposal of shedder residue is becoming more costly. In addition, coatings and galvanization contaminate steel scrap—a major revenue producer for scrap yards— and thus lower its value. If a viable system of recycling logistics is expected to exist, issues such as separation, disassembly, and material reprocessing must be considered in the design, product engineering, and material selection activities of the product design cycle.[43]

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[41] Ibid.

[42] Robert Eller, "Japanese Update," *Modern Plastics Encyclopedia '93* (New York: McGraw-Hill, 1992), 40-43.

[43] See Gillespie, Kaplan, and Flynn, op. cit.

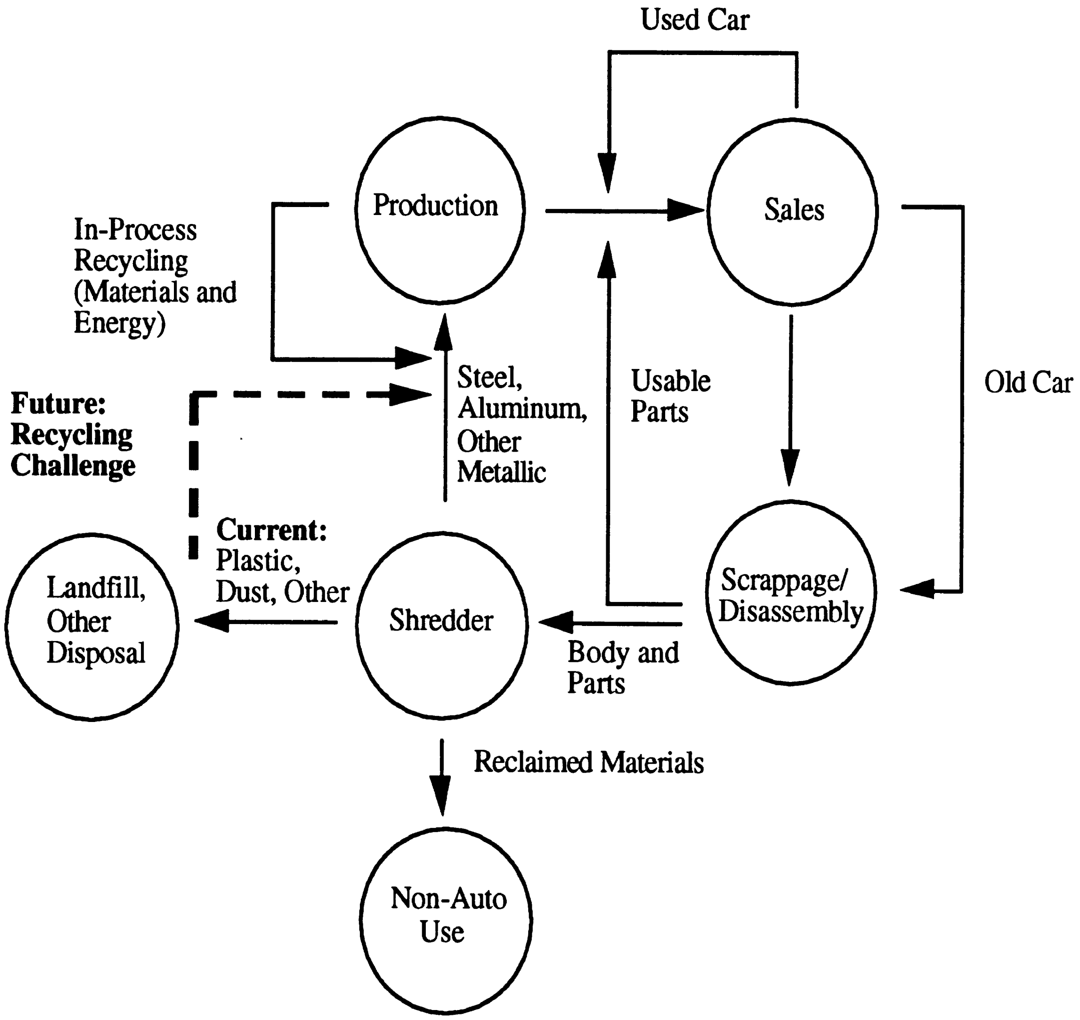

Figure 6 Flows of Energy, Materials and Value in the Automotive Life Cycle

With regard to postconsumer material disposition, Dr. J. Williams in his paper "Impacts of Disposal Issues on Vehicle Design Procedures" outlines key material selection and vehicle design issues. These considerations are driven by the concept shown in figure 7—as the opportunity for post material usage increases, the present value of those materials increases.[44] The cost of dismantling may rise with the level of value. The objective is to keep the benefit (the material value added) above the additional cost of disassembly. Or, the objective is to keep the value of a scrapped vehicle positive. "On the face of it these modest savings for the customer appear to offer little scope. Therefore a heightened awareness must be created among customers so that they are prepared to accept a higher price for greater protection of the environment. Yet

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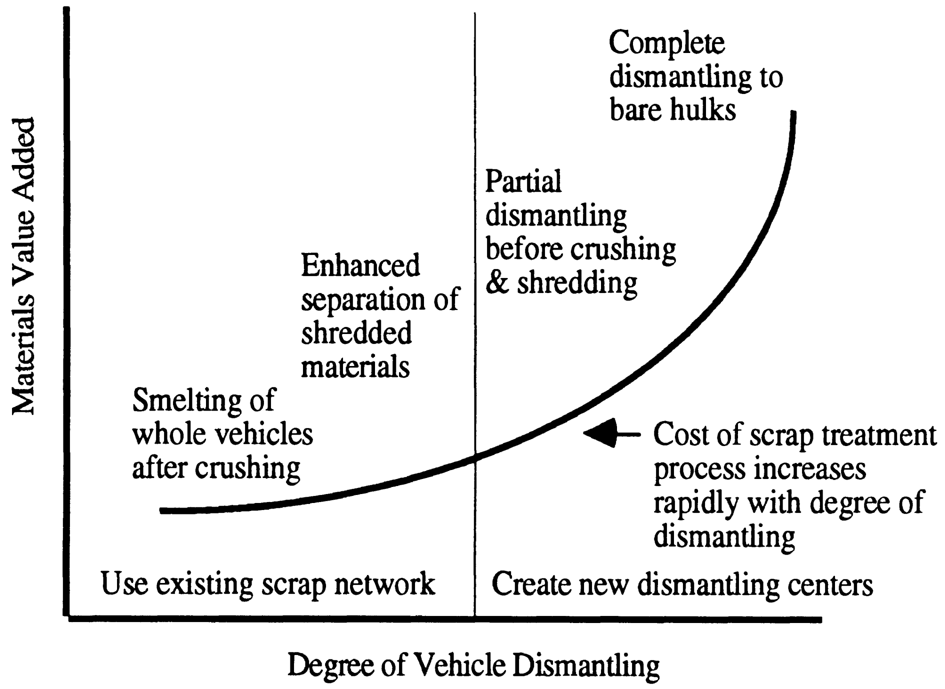
[44] J. Williams, "Impacts of Disposal Issues on Vehicle Design Procedures," *AutoTech 1991.*

if ongoing political discussions result in higher fuel prices and waste disposal charges, then pure cost/benefit assessments will support efforts aimed at weight reduction and the utilization of closed material cycles."[45]



Source: Williams, "Impacts of Disposal Issues on Vehicle Design Procedures

Figure 7 Amount of Vehicle Dismantling versus Material Value Added

Design for disassembly and material selection, Williams claims, will require the greatest attention to minimize postconsumer disposal streams. Component designs, fastening systems, and packaging will need to adapt to disassembly requirements. Driven by public demand and regulatory expectations (using 25 percent recycled content is a 1994 European goal, not requirement), European manufacturers are leading the efforts to apply disassembly concepts in production vehicles. "(In Europe,) BMW, Volkswagen, and Peugeot have instituted recycle-content programs, and are operating pilot plants for car disassembly. BMW announced a parallel program in the U. S. whereby cash incentives are paid for trade-ups in which the old vehicle is

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[45] Walzer, op. cit.

returned to a dismantling center."[46] The Big Three, under the auspice of USCAR, has announced the development of a joint recycling research center. The initial plan is for dismantling of up to 500 vehicles per year.

Increased recycling may restrict the application of certain materials and reduce the number of discrete materials used in any one system.[47]

> A balance must exist between the benefits of standardization—lower cost and improved recyclability—and the drawbacks to consumer appeal of producing a non-differentiated style in cars. Both Japanese and European auto makers have demonstrated a stronger commitment to broad use of polypropylene than U.S. OEMs, applying specialized grades for bumpers, instrument panels, interior trim, and other parts rather than relying on ABS, nylon, and other resins. As a competitive issue, foreign car manufacturers have achieved a distinct edge over their U.S. counterparts in establishing formal plastics standardization and recycling programs.[48]

Considering current recycling experience, economics, and public policy, increased use of plastics will require reducing the number of types of thermoplastics used within any one system, marking component material types, and designing for dismantling. [49]

CURRENT MATERIAL SELECTION PRACTICE

Historic Trends of Material Usage Per Vehicle Table 4 provides a 12-year perspective on automotive weight trends. While total weight has changed by less than seven percent over the last 12 model years, specific material usage has changed dramatically. For example, between 1980 and 1992, conventional steel usage has dropped 20.6 percent. During the same time period, plastics and composite usage has risen by 24.6 percent. Each individual change is driven by a specific set of circumstances. Each of the issues discussed in this paper (markets, regulation, business constraints, and others) contribute to the net result presented in table 4. Specific issues are discussed in the following section and are cataloged in appendix 1.

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[46] The Kline Company, "The World Plastics Industry Today," *Modern Plastics Encyclopedia '93* (New York: McGraw-Hill, 1992), 19-32.
[47] Williams, op. cit.
[48] The Kline Company, op. cit.
[49] Walzer, op. cit.

Table 4
Automotive Material Usage
1980 to 1992 Model Year
(in pounds)

Material	1992	1991	1990	1989	1988	1980
Conventional Steel	1,379.0	1,341.0	1,246.5	1,416.0	1,440.0	1,737.0
High Strength Steel	247.0	240.5	233.0	234.0	232.0	175.0
Stainless Steel	41.5	37.0	31.5	31.0	31.0	27.5
Other Steels	42.0	41.5	53.0	47.0	45.0	54.0
Iron	429.5	431.0	398.0	459.0	457.0	484.0
Aluminum	173.5	166.0	158.5	155.5	149.0	130.0
Rubber	133.0	135.5	128.0	134.5	134.0	131.0
Plastics/Composites	243.0	236.0	222.0	224.5	223.0	195.0
Glass	88.0	86.0	82.5	85.0	85.0	83.5
Copper	45.0	45.0	46.0	49.5	49.0	35.0
Zinc die castings	16.0	17.5	19.0	20.0	19.5	20.0
Powder Metal Parts	25.0	23.5	23.0	21.5	n/a	17.0
Fluids and lubricants	177.0	174.0	167.0	179.5	178.0	178.0
Magnesium castings	6.5	5.0	n/a	n/a	n/a	1.5
Other materials	89.5	70.5	88.0	83.0	124.5	94.5
TOTAL	**3,135.5**	**3,059.0**	**2,896.0**	**3,140.0**	**3,167.0**	**3,363.0**

Source: Wards Automotive Year Books 1993, 1991, 1989, and 1981.

Issues Influencing the Application of Specific Materials This section identifies major issues and recent product decisions that influence a material's total automotive demand.

Steel With the introduction of many new models and facelifted vehicles, domestic auto makers have shown that the 1990s may become the "bigger is better" decade. Consumers have demanded larger and roomier vehicles, translating into an increase in steel usage. In fact, depending on the sales mix, overall steel content almost reached 1,750 pounds per vehicle for 1992, a level close to the mid-1980s. While the level is close, it is 243.5 pounds less than the total 1,993.5 pounds of steel consumed per average U.S.-built vehicle in 1980. Use of two-sided electrogalvanized steel has steadily increased over the past five years, as auto makers furthered their efforts to improve rust protection. This application began when auto makers were looking to improve the durability of their vehicles with precoated steel, a material with more corrosion resistance characteristics than most others.

Plastics Plastic applications have grown tremendously over the last decade, causing the consistent yearly increase in plastic usage. Plastic fuel tanks, which weigh around 30 percent less than their conventional steel counterparts, and plastic bumpers, which meet federal regulations and shave off 30 to 40 pounds per vehicle, were a couple of the first major applications. The big news for plastic was the 1990 introduction of GM's new minivans, which became the world's first high-volume vehicles with all-plastic skins. Some domestic auto makers have also shifted to plastic fenders on their cars, citing resistance to corrosion, recoverability from parking lot dents and weight savings as the main reasons for their change. However, it appears that these gains may be short-lived as GM is looking to revert back to steel on its APV vans and Chrysler is rumored to be converting away from plastic on its LH platform fenders.

Aluminum The material of the 1990s, as many experts predict, has seen rapid growth in engine-related applications. The 1989 Chevrolet Corvette ZR1 engine became the most aluminum-intensive U.S. powerplant for passenger car use. Foreign auto makers followed by introducing all-aluminum engines on some of their luxury models. Aluminum wheels, typically weighing only 20 to 25 pounds each, were introduced across broad product lines in the late 1980s contributing to aluminum's dramatic application rise. In 1991 Honda unveiled the Acura NSX, which had made aluminum its primary material. Although sales of this expensive sports car are disappointing, it remains one of aluminum's most significant showcases. Another significant application for aluminum is in the reinforcement bars on bumper systems. Aluminum usage is expected to increase due to the expected tougher federal regulations on CAFE during this decade.

Powder Metal Ford has remained the leader in powder metal applications. The company recently switched camshafts from steel to composite metal in its modular engines. For 1991, the industry average was around 23 pounds of powder metal, yet a Lincoln Town Car equipped with the 4.6 liter, modular, V-8 engine, has approximately 40 pounds of powdered metals.

Magnesium Much of magnesium's increased application is as a replacement for aluminum in engines. The most significant jump for magnesium, however, has come from its use in GM's Northstar powertrain, first introduced for use in the 1993 Cadillac Allanté. Weighing 33 percent less than an equal volume of aluminum, and 70 percent less than zinc, magnesium was used in the induction system, valve covers, oil filter adapters, and other major engine components, totaling 15 pounds per engine. A torque converter in the automatic transmission teamed with this engine is also made from magnesium. Die cast magnesium has seen an increase due to its use for steering column and brake/clutch supports on some GM cars.

Iron Iron's weight disadvantage has been a major contributor to its decreasing use in the auto industry. In the late 1980s, however, lightweight iron components began to hit the market. Thin-walled VAC (vacuum assisted casting) iron exhaust manifolds were used on some GM engines in 1988. Furthermore, this casting process may allow iron to remain in certain applications that otherwise would have shifted to aluminum or stainless steel due to iron's weight disadvantage. Yet, when auto makers became concerned about the noise, vibration, and harshness of their engines as the 1990s began, thicker cast-iron engine sections were used as a solution. While auto makers prefer the reliability and durability of iron, toughening CAFE standards will benefit lightweight materials.

Copper Aluminum competition had hurt copper use, but recent increased use of electrical components, such as harnesses, wires, and motor windings, has meant a significant increase for copper applications. Some new applications include power windows/door locks, stereo systems, rear defoggers, and antilock brakes. When electrical applications are considered, along with copper's use as an alloying agent, the copper content in U.S.-built cars has increased by over 10 pounds since 1980. However, the use of copper radiators continues to decline, as more auto makers are switching to aluminum to help reduce vehicle weight.

Stainless Steel The use of stainless steel rose 11 percent in 1992 over 1991 levels. This sharp rise reflects the use of stainless steel in new applications, such as fuel lines, connectors, and trim components. GM opted to use stainless steel on the longer exhaust pipes of some of its cars, as well as switching from aluminized steel to stainless steel exhaust systems on a number of its vehicle lines. GM cited the durability of stainless steel as the reason for the move. Another application for stainless steel has been in the canisters of the airbag systems now used by auto makers.

CONCLUSION

Material selection in the automobile industry is an artful balance between market, societal, and corporate demands. The vehicle manufacturers' materials engineer and component-release engineer play the pivotal role in screening, developing, validating, and promoting new materials. The material selection process itself will evolve as vehicle and component development processes change to become more responsive—in terms of accuracy, time, and cost—to market and regulatory demands. This paper describes the process as material and component suppliers will find the system today. Some thirty criteria used in material selection are identified. How critical any one attribute is depends upon the desired performance objective. The interrelationships among objectives, such as fuel economy, recyclability, and economics, are sufficiently strong that the materials engineer is always balancing simultaneous needs. How the equations of market, societal, and corporate demands are balanced determines specific automotive material usage.

APPENDIX I

Identification of Major Parts by Material and Process

	Primary Materials	Primary Process	Driving Forces
Engine			
Block	Iron Aluminum	Casting	Fuel Economy Weight Reduction Cost Reduction
Cylinder Head	Aluminum Iron	Casting Machining	Fuel Economy Cost Reduction Performance
Intake Manifold	Plastic Aluminum	Casting Molding Machining	Fuel Economy Weight Reduction Formability
Connecting Rods	Powder Metal Steel	Molding Forging Machining	Weight Reduction Durability
Pistons	Aluminum	Forging Machining	Weight Reduction Durability
Camshaft	Iron Steel Powder Metal	Molding Forging Machining	Fuel Economy Durability
Valves	Steel Magnesium	Stamping Machining	Cost Reduction Fuel Economy Durability
Exhaust System	Stainless Steel Aluminum Iron	Extruding Stamping	Cost Reduction Fuel Economy Packaging

	Primary Materials	Primary Process	Driving Forces
Transaxle			
Transmission Case	Aluminum Magnesium	Casting Machining	Fuel Economy Weight Reduction Cost Reduction
Gear Sets	Steel	Blanking Machining	Fuel Economy Durability
Torque Converter	Magnesium Steel	Stamping Casting	Fuel Economy Cost Reduction
CV Joint Assemblies	Steel Rubber	Casting Forging Extruding Stamping	Cost Reduction Quality Durability

	Primary Materials	Primary Process	Driving Force
Body Structure			
Body Panels	Steel Plastic Aluminum	Stamping Molding	Weight Reduction Formability Durability
Bumper Assemblies	Plastic Steel Aluminum	Stamping Molding	Damagability Formability Weight Reduction

Appendix 1 (continued)

Identification of Major Parts by Material and Process

	Primary Materials	Primary Process	Driving Force
Chassis/Suspension			
Steering Gear/ Column	Steel Magnesium Aluminum	Casting Stamping Forging Machining	Packaging Drivability Weight Reduction
Rear Axle Assembly	Steel Plastic	Stamping Molding	Ride Quality Cost Reduction
Front Suspension	Steel Aluminum	Stamping Forging	Cost Reduction Drivability
Wheels	Aluminum Steel	Stamping Forging	Weight Reduction Cost Reduction Formability
Brakes	Steel Friction Materials	Stamping Forging Misc. Fabricating	Weight Reduction Durability Performance

	Primary Materials	Primary Process	Driving Force
Seats/Trim			
Seats	Steel Fabric Foam	Molding Stamping	Comfort Weight Reduction
Instrument Panel	Plastic Steel Foam	Stamping Molding	Formability Weight Reduction Cost Reduction
Headliner/Carpeting	Synthetic Fiber	Molding	Cost Reduction Quality
Exterior Trim	Plastic Aluminum Zinc Die Casting	Molding Casting Stamping	Formability Weight Reduction Durability

	Primary Materials	Primary Process	Driving Force
HVAC System			
A/C Compressor	Aluminum Steel Plastic	Casting Molding Stamping	Weight Reduction Formability Cost Reduction
Radiator/Heater Core	Copper Aluminum Plastic	Extruding Molding	Weight Reduction Durability
Engine Fan	Plastic Steel	Stamping Molding	Weight Reduction Durability