

PLASTICS AND COMPOSITES IN AUTOMOBILES:
A TECHNOECONOMIC ASSESSMENT OF CAUSES AND EFFECTS OF INNOVATION

by

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BARBARA POGGIALI

submitted to the Department of Materials Science and Engineering
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Abstract

This thesis analyzes the increased consumption of engineering plastics and composites in structural and semi-structural components of U.S.-produce automobiles in 1981-1986, and focusses on the history of the innovation processes of materials suppliers. The research traced the innovations for a sample of case studies of structural and semi-structural components currently made with new polymeric materials technology. The value and volume of engineering plastics and composites consumed in structurally demanding applications were calculated.

Three forces that could drive materials consumption were identified as: 1) economic factors (i.e., factor prices like price of raw materials and labor); 2) materials and/or process innovations; and 3) perceived needs of the automotive companies. Factor prices were too constant to be influential over the time period studied; innovations in materials and processes that occurred during this time period were identified.

The materials supplier was seen to bear the burden of innovating over the materials user. Hypotheses generated to explain why found that supplier innovation was spurred by a perceived need for new materials and processes. Technical feasibility was not sufficient to spur adoption of plastics and composites: only perceived demand from the automotive companies brought innovation to fruition. This need arose because imported cars made significant inroads on sales of U.S. produced automobiles during the energy crises of the 1970's.

The length of a materials supply contract apparently did not affect innovation, but development contracts with suppliers encourage supplier innovation because of the possibility of single sourcing. Because of the large market potential to the supplier, the automotive company can dictate innovation.

The results of this work clarify how suppliers can successfully develop innovative materials for large volume, structurally demanding applications. Supplier innovation clearly played a dominant role in the adoption of plastics and composites in U.S. automobiles, but only as a result of the receptiveness of the automotive companies. Supplier involvement can be further fostered through development contracts leading to single sourcing.

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1. INTRODUCTION

Because of considerable interest in using engineering plastics and composites in demanding applications in automobiles, the consumption of these materials has increased from 5 million dollars to over 70 million dollars between 1981 and 1986.

This thesis will examine the sharp increased usage of engineering plastics and composites in structurally demanding automotive areas. If the industry is at the beginning of an S-shaped growth curve, it should be of interest to polymeric materials suppliers facing competition for a new and potentially large market.

Chapter 2 documents the change in the consumption pattern of polymeric materials in the markets selected for research. Selected parts of the automobile are being investigated because of trends in usage of advanced polymeric materials in those same applications.

Chapter 3, "Methodology", introduces the methodology used to explain the sudden adoption of plastics and composites in automobiles. Case studies generated the hypotheses that explain the increase in consumption. Three classes of explanations are introduced, which relate to economic factors and technological change that affected the automotive industry.

Chapter 4, "Factor Prices", discusses the first possible cause of plastic materials substitution by analyzing materials and labor pricing trends. The

decrease in raw materials prices, as well as a change in labor rates, could influence the attractiveness of a new material. Data showed that no major fluctuations occurred in factor prices demonstrating that adoption of advanced plastic materials was not influenced by factor prices.

Chapter 5 discusses technological innovation, including the criteria for innovating. The new part had to be cost competitive with the metal part it was substituting, and had to meet performance requirements that could not be met before with plastics. This chapter further details the technological innovations, with particular emphasis on who (which functional group, i.e., materials supplier or the automotive firm) initiated the innovation and who funded it. From each case study, as well as through interviews, those factors and conditions necessary for successful development of engineering plastics and composites in structural and semi-structural automotive applications were determined. Details for each case study are presented in Appendix A.

Chapter 5 compares by cost analysis the innovative part versus the traditional part. Some cases were analyzed using cost models which estimate processing costs based on technical and economic inputs. Other cases were analyzed by comparing data obtained from the producers or the auto firm for competitive materials. Details of the cost modeling methodology are presented in the Appendix C.

Chapter 6 investigates the factors causing innovations. The innovations were stimulated by the perceived demand for materials, processes and compo-

nents with the characteristics exhibited by the new developments. An attempt is made to measure this "demand".

Chapter 7 discusses mechanisms materials suppliers use to innovate and to recover some of the costs of innovating. Factors of interest include: the length of a supply contract, the existence of a development contract, utilization of existing resources and the creation of an automotive market support structure.

Chapter 8 applies the research results to understand near-future developments of engineering plastics and composites in automotive areas, particularly strategies that may be useful to materials suppliers. Part-for-part substitution, although not optimal, is still the most likely approach to introduce a new material. It was found imperative that the innovative part not increase the automobile system cost. It is equally important that the demand for the innovation be well understood, an aspect of innovation that is discussed with respect to a case of composite parts that failed because the supplier did not fully comprehend the needs of the customer.

Substantial data were gathered on each case study. The data are compiled in Appendix A. Appendix B is a brief description of the supplier-manufacturer relationships within the automotive industry. Appendix B lists examples of firms involved in the U.S. automotive industry. Appendix C contains a brief discussion on the cost modeling methodology applied extensively throughout this research, and how the models can be

used to analyze technological change. Appendix D lists the people who were interviewed, and their company affiliation.

2. CONSUMPTION OF ENGINEERING PLASTICS AND COMPOSITES IN AUTOMOBILES

2.1 DEFINITION OF THE MARKET SEGMENT

This research studies the consumption pattern of engineering plastics and composites in innovative automotive applications in the U.S.A.. These innovative applications can be broadly defined as structural and semi-structural automotive components that must meet stringent performance requirements. Structural and semi-structural applications in cars were selected as the market segment for examination in this work because they have recently undergone much development [3, 17, 18, 21, 23, 30, 32, 48, 49, 50, 51].

Plastics have been used in transportation applications for over a decade, mostly for trim, dashboard and interior components; the emerging area of structural/semi-structural application of plastics was chosen because of their demanding structural performance requirements.

In this thesis, the term "performance requirements" will be used to encompass all characteristics of the component, sub-assembly or system which affect its acceptability for substitution of a previously existing part. These are functional requirements, i.e., they are characteristics which describe the component in terms of what it has to do. For example, important performance requirements for a body panel, irrespective of material used, include corrosion resistance, class-A surface, weight, and cost; for leaf springs, an especially important parameter is fatigue life, as well as

weight and cost; for bumper systems, impact resistance is paramount, as required by the Federal Motor Vehicle Safety Standards.

Structural areas refer to load-bearing and/or energy management components. Examples of these are: bumper systems (as opposed to bumper fascia) and leaf springs. Semi-structural areas, on the other hand, refer to body panels. These are some of the applications in which engineering plastics and composites have penetrated in recent years.

2.2 DATA ON CONSUMPTION

Published data on consumption in these areas in automobiles were collected from various sources including: Automotive News, the Society of the Plastics Industry, and Wards Automotive Yearbook [53, 62, 63]. The available data, however, were judged too aggregated and often inconsistent from source to source. It was found especially difficult to trace past consumption figures: the same journal would publish consumption of reinforced materials in all vehicles one year, and thermosetting materials in light trucks another year, thus making it impossible to trace specific consumption patterns.

Therefore, as part of this study, it was necessary to make estimates of the actual usage of engineering plastics and composites in structural and semi-structural areas for the last several years. The estimates (shown in Figure 1 on page 16 through Figure 4 on page 19) were based on the weight of the component and on the number of vehicles produced that incorporate

the component. Figure 5 on page 20 shows the trend of total automobile production in the same years, to provide a context in which to examine the change in materials consumption.

Figure 1 on page 16 and Figure 2 on page 17 display the volume (in lbs/year) of plastic and composite material actually used in U.S. automobiles and vans, whereas Figure 3 on page 18 and Figure 4 on page 19 show the value (in \$/year) of the materials used. The dollar value of the materials is based on the estimated volumes of material used, and their average price assumed for the calculations as listed in Table 1. However, the estimates do not account for the use of these materials in prototypes or other experimental programs, and they do not take into account rejects and failures. They are therefore conservative estimates: they include only the material that was consumed in parts that are actually in use.

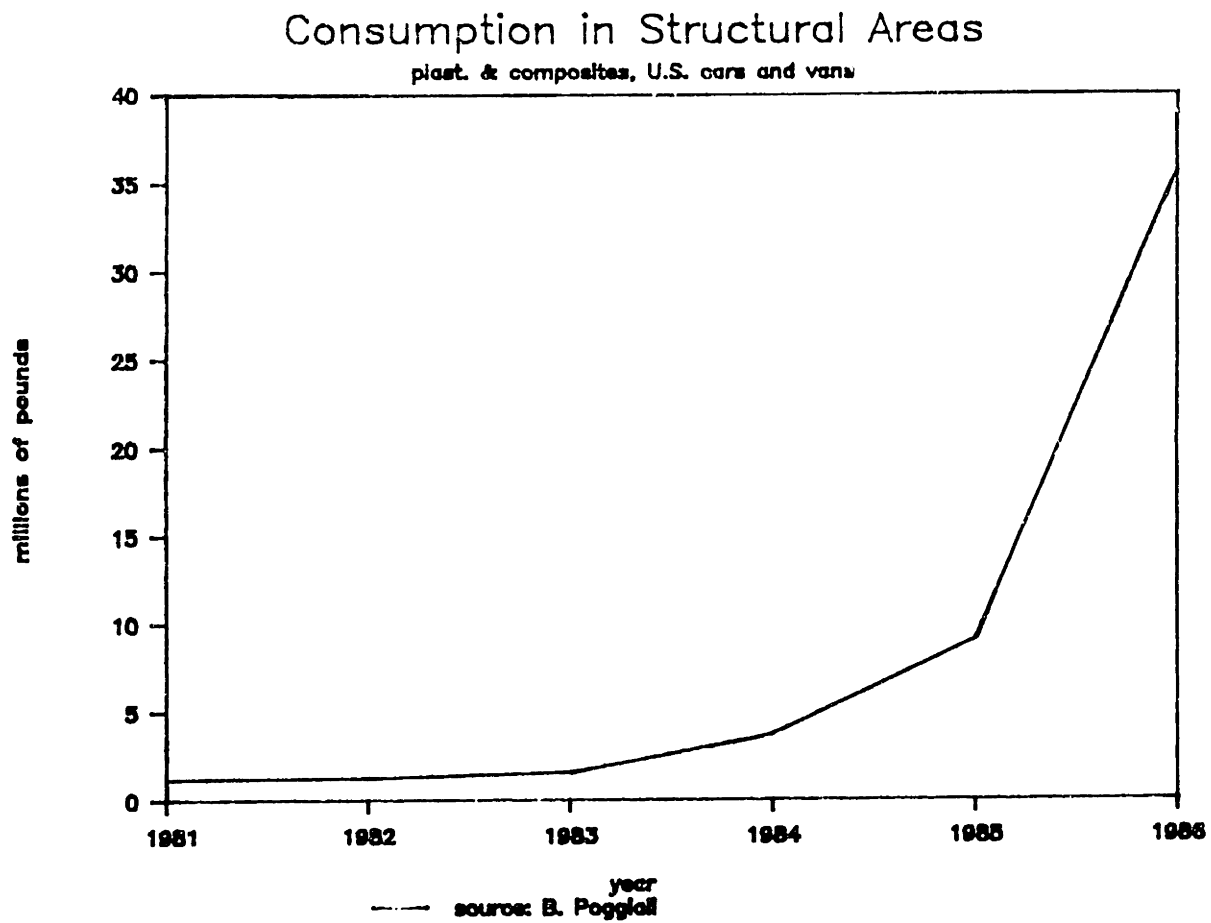


Figure 1. Consumption of plastics and composites in structural areas

Consumption in Automotive Skins

plast. & composites, U.S. cars and vans

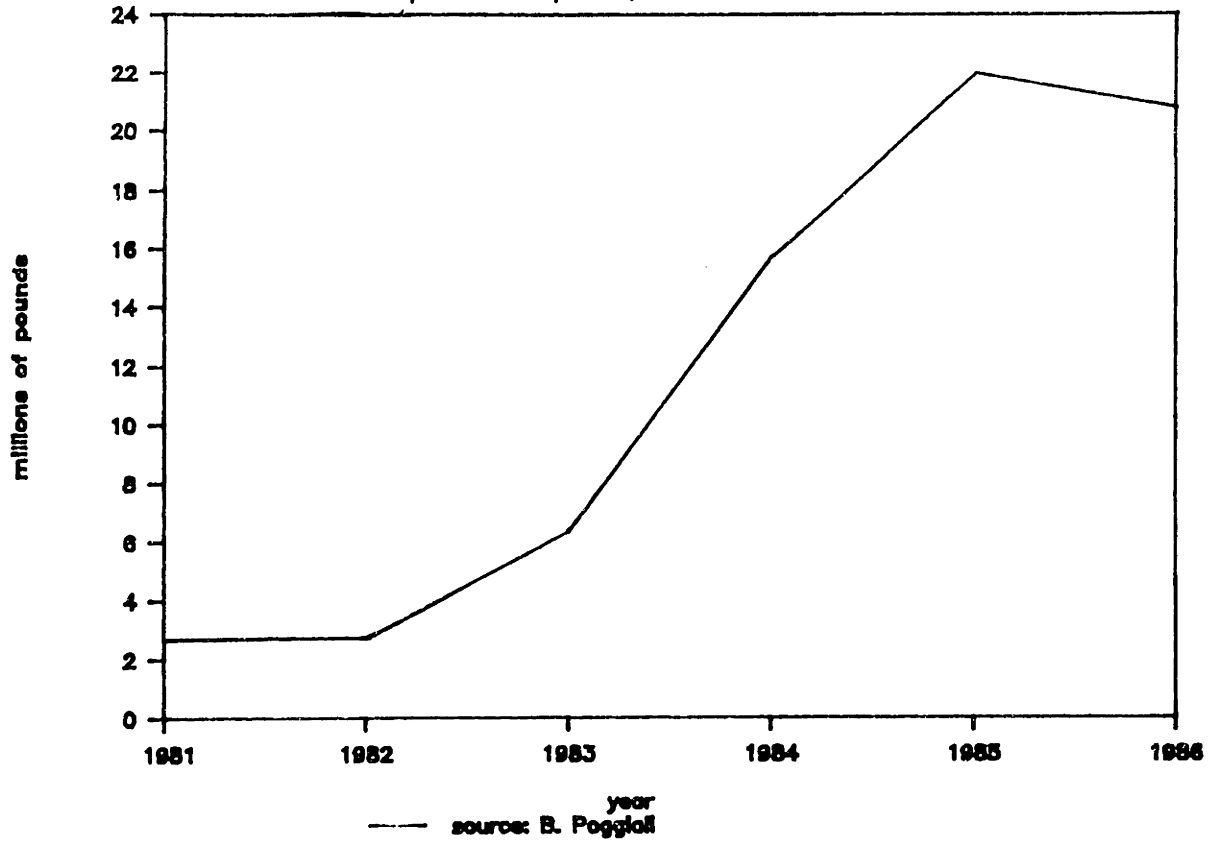


Figure 2. Consumption of plastics and composites in automotive skins

Value in structure and skins

plast. & composites, U.S. cars and vans

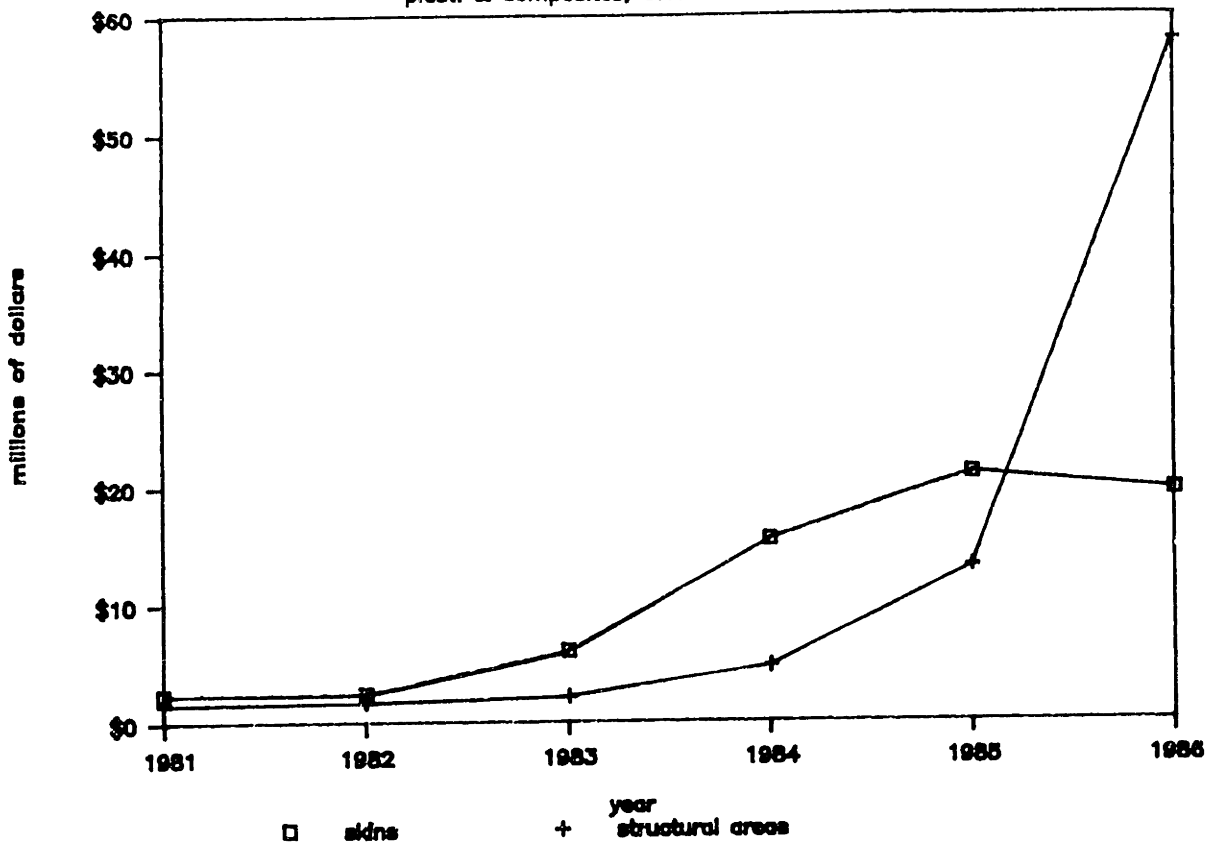


Figure 3. Value of plastics and composites in structure and skin

Total value of plastics and composites

U.S. cars and vans

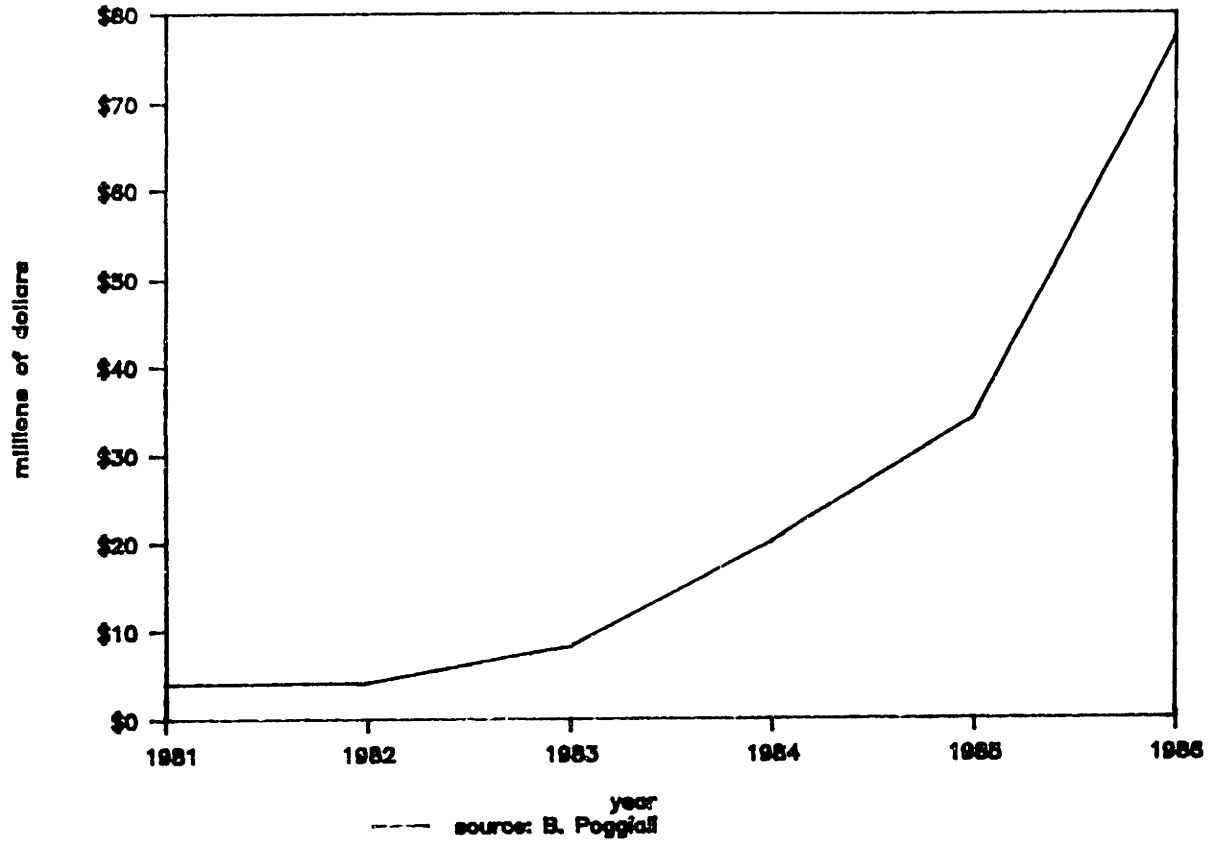


Figure 4. Total value of plastics and composites in U.S. cars and vans

Production of autos in the U.S.

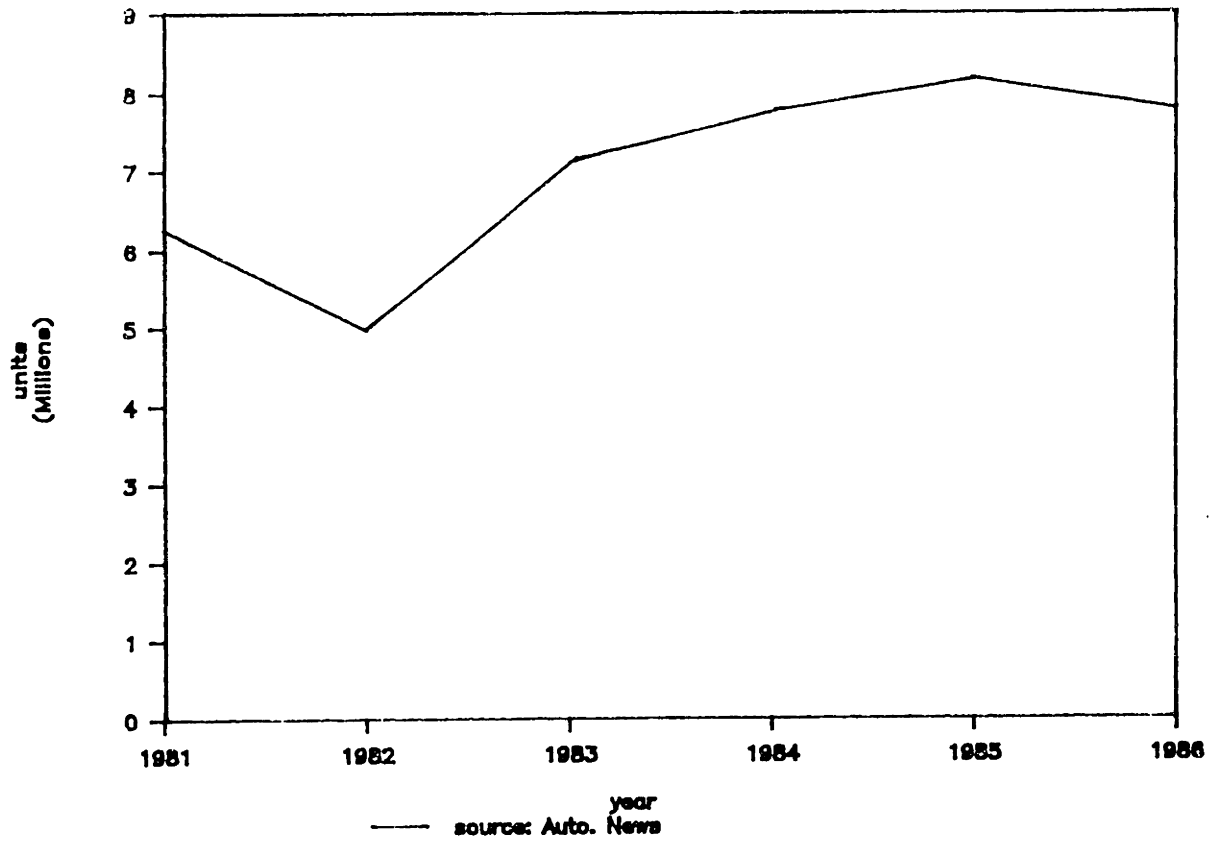


Figure 5. Trend in U.S. automobile production

TABLE 1 - AVERAGE RESIN PRICES USED TO CALCULATE VALUE OF CONSUMPTION

Materials	price/lb
SMC	\$0.90
RIM polyurethane	\$1.00
Xenoy	\$1.80
Bexloy C	\$2.00
Azdel PP	\$1.12
65% glass/epoxy	\$1.34

The consumption figures start in the year 1981. This is because prior to that year there were no "advanced" plastics in demanding applications in automobiles.¹

Figure 1 on page 16 shows the consumption of engineering plastics and composites in structural areas in passenger cars and vans for the years 1981 to 1986. The structural areas represented are: bumper beams, bumper systems, load floor, and leaf springs. The figure indicates little growth until the year 1983. During this period, the Chevrolet Corvette and the Ford Econoline van had the only notable structural application - glass-reinforced composite leaf springs, which range in weight from 8 lbs. (3.6 kg.) to 10.5 lbs. (4.8 kgs.).

¹ Advanced plastics refer to those materials whose properties are tailored to specific engineering requirements.

A glass-reinforced composite bumper beam was introduced in the Corvette in 1984, each weighing about 12 lbs. (5.5 kgs.). A glass-reinforced composite leaf spring was also introduced in General Motor's Astro Van, also in 1984. These two applications contributed to a slight increase in the usage of composites in automobiles.

The Ford Taurus and Sable cars and the Aerostar van employ bumper systems made entirely out of plastic that weigh between 21 and 23 lbs. (9.6 to 10.5 kgs.). As well, the station wagon versions of the Taurus and Sable employ reinforced plastic load floors, that weigh about 30 lbs. (13.6 kgs.). These new applications have more than doubled the usage of these novel materials in passenger vehicles.

A greater increase over 1985 is observable in 1986 as the result of the use of reinforced thermoplastic bumper beams and leaf springs in the Cadillac Eldorado and Seville. As well, the Taurus and Sable, which began production at the end of 1985, were manufactured in much larger quantities in 1986.

Figure 2 on page 17 shows the usage of engineering plastics and composites in the skins of U.S. passenger cars and vans. The Corvette was the only vehicle with a composite skin, (containing approximately 120 lbs. (55 kgs.) of composite material) prior to 1982. Although the The Corvette fiberglass panels introduced in 1953 were not considered "advanced plastics" applications by industry experts. They were made by hand lay-up techniques requiring significant amounts of labor. The inadequate surface quality of

the panels demanded a significant amount of manual sanding after the part was made.

When the Pontiac Fiero began production near the end of 1983, the consumption of plastics in automotive body panels doubled in the next year. Plastic materials in the Fiero exterior weigh on the order of 100 lbs. (45.5 kgs.) per vehicle depending on the model and year.

Beginning in 1985, the Ford Aerostar, the Cadillac Eldorado and Seville, and the Olds Firenza employed SMC (glass/polyester sheet molding compound) in such external areas as the hood.

The limited growth in plastics consumption for body skins in the year 1986 results from a slight reduction in the number of vehicles produced in 1986 and the lack of new plastics applications.

Overall, the total value of plastic materials in the engineering applications in passenger vehicles described previously, has increased from less than 5 million dollars in 1981 to over 77 million dollars in 1986 (Figure 3 on page 18 and Figure 4 on page 19).

The data clearly indicate a sharp change in the consumption of engineering plastics and composites in structural and semi-structural automotive applications. The possible technical and economic causes for this shift in consumption are examined in the following chapters.

3. METHOD

This thesis will offer an explanation for the sharp increase in engineering plastics and composites applications in automobiles, using a series of case studies where innovative plastic and/or composite components in automobiles have recently replaced their steel counterparts. Each case studies the development of both the material and the process used to fabricate the component, and, as well, investigates the design and manufacturing parameters necessary to implement the innovation. A series of hypotheses and potential explanations for the phenomenon based on the data from the case studies were generated.

3.1 SAMPLE

The sample (i.e., the case studies) is an exhaustive one, consisting of components that are (i) currently made of engineering plastics and composites, (ii) are under serious development, or (iii) have been used in large volumes. The sample consists of components which are either structural or semi-structural, according to the definition given earlier.

The sample comprises the following components:

- transverse leaf spring,
- longitudinal leaf spring,
- all-thermoplastic bumper system,
- thermoplastic composite bumper beam,

- composite hood,
- thermoplastic vertical body panel,
- RIM body panel,
- amorphous nylon rear quarter panel,
- composite tailgate,
- thermoplastic composite load floor, and
- composite driveshaft.

Data on each application, summarized in Table 2, show the material and the process used in each case. These data reflect the processes used to produce advanced polymeric components, and the materials of interest.

TABLE 2 - SUMMARY OF CASE STUDIES

PROJECT	PROCESS	MATERIAL
composite driveshaft	filament winding	epoxy/ glass, carbon
transverse leaf spring	filament winding + compr. molding	epoxy/ glass
longitudinal leaf spring	filament winding + compr. molding	epoxy/ glass
all-thermoplastic bumper system	injection molding	PC/PBT blend
thermoplastic composite bumper beam	compression molding	PP/ continuous glass
composite hood	SMC molding with in-mold coating	polyester/ chopped glass
thermoplastic vertical body panel	injection molding	PPE/nylon blend
RIM body panel	reaction injection molding	polyurethane with IMR
amorphous nylon rear quarter panel	injection molding	amorphous nylon blend
composite tailgate	SMC molding	polyester/ chopped glass
thermoplastic composite load floor	compression molding	PP/ continuous glass

The processing techniques used are:

- filament winding,
- injection molding,
- SMC (compression) molding,
- high-speed thermoplastic stamping, and
- reaction injection molding (RIM).

The materials used can be categorized as follows:

- thermoset matrix/continuous reinforcement composite,
- thermoset matrix/chopped reinforcement composite,
- thermoplastic matrix/continuous reinforcement composite,
- 2-component RIM system, and
- thermoplastic polymer alloy.

It was found that in each case, technological innovations had occurred (i.e. advances had been made in the technology). These were explored further, based on the theory/assumption that innovations are associated with a potential to capture benefit [42, 44] (for example, materials suppliers might wish to innovate in order to increase sales). It was also found that, for the majority of the cases studied, the innovation was developed by the materials suppliers. The innovations are discussed in Chapter 5, and details on each case are included in Appendix A.

3.2 HYPOTHESES

Several hypotheses that could account for the sudden increase in the use of advanced polymeric materials in the automotive industry, were explored.

The hypotheses fall into two broad categories: those related to variations in the price of exogeneous factors such as labor rates and raw materials prices (termed "factor prices" throughout this thesis); and those which reflect other "events" in the industry, including the development of innovative technology.

The lack of significant fluctuations in the price of raw materials or labor, led to the conclusion drawn in Chapter 4 that factor prices have not affected the substitution of new materials.

The next set of hypotheses question whether technological innovations caused the use of advanced plastics in the areas discussed previously, or whether they were used as the result of advances in their properties and/or processing. It was relevant to investigate whether advanced structural or semi-structural plastics technology existed prior to its use in the early 1980's in the automotive industry, and, if so, why it had not yet been employed for automotive applications.

The hypotheses also attempt to explain the behavior of the various groups involved in the automotive industry, and in particular of the plastic materials suppliers who bore much of the burden of innovating. The first and

foremost reason for the supplier's involvement was the potentially huge market for their resins. Other factors to explain supplier involvement were identified. They did not cause the use of plastics and composites in automobiles, but they reflect a changing structure of the supplier-user relationship. This is discussed further in Chapter 6.

To summarize, a set of case studies were performed to generate hypotheses and explanations for the observed increase in engineering plastics and composites consumption in automobiles. Technological innovations were observed, with particular emphasis on which functional group (i.e., the materials supplier or the auto firm) initiated the innovation and who funded it. From each case study, as well as through other interviews, it was possible to understand which factors and conditions were necessary for the development of the new applications of advanced polymers in the automotive industry.

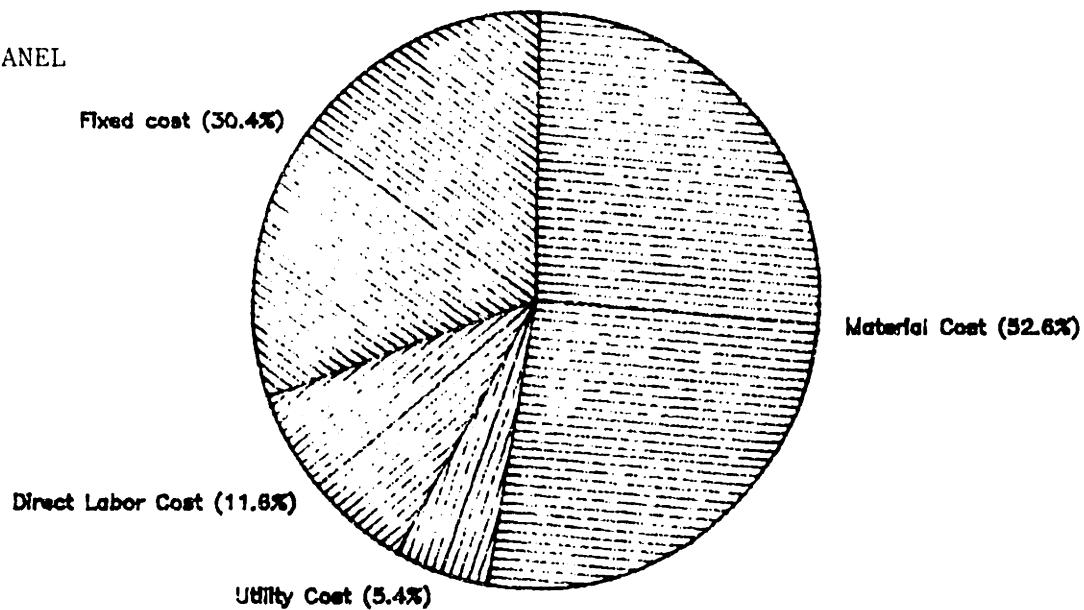
4. FACTOR PRICES

The fluctuations among factor prices were investigated, and the observed trends are presented here. A decrease in raw materials prices, as well as a change in labor rates, would influence the attractiveness of a new material, as both of these contribute to the cost of a component. For example, the cost of making a panel out of SMC (sheet molding compound) is approximately 53% materials, 12% labor, 5% energy, and 30% capital, and the cost of an equivalent steel panel is approximately 53% materials, 12% labor, 0.3% energy, and 35% capital, as demonstrated in Figure 6 on page 31. The data for this Figure were obtained from two cost models (see Appendix C) for SMC molding and for steel stamping, demonstrating that labor and materials make up a significant portion of the piece cost, such that a change in one of the factor prices could affect the attractiveness of a new material/process.

The aim of tracing factor price histories was to observe whether changes in factor prices corresponded to changes in the consumption pattern of engineering plastics and composites. Data showing that no major fluctuations occurred in these factor prices are presented and discussed, demonstrating that factor prices were not a significant influence in the adoption of advanced polymeric materials in automobiles.

Data on the price of the resins and labor wages start a few years prior to the estimated consumption figures, to take into account the fact that decisions to substitute a material or a process would be made prior to the sub-

SMC PANEL



STAMPED STEEL PANEL

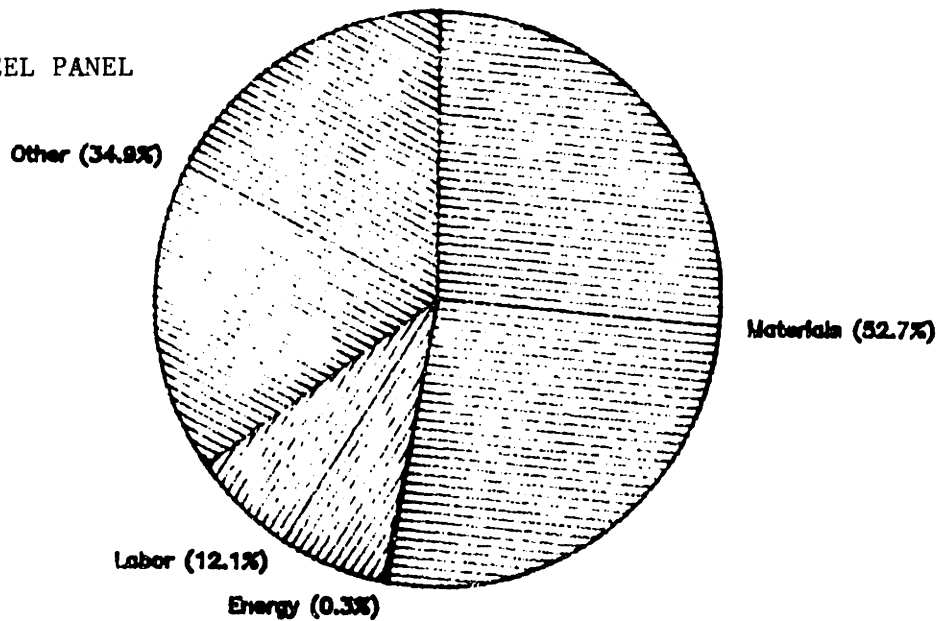


Figure 6. Total cost breakdown for a plastic and a steel automotive panel

stitution actually being visible in production. Therefore, it was postulated that if changes in the factor prices had caused a shift in the consumption of the new materials, the material substitution would have followed the change in factor prices.

4.1 PRICE OF THE RAW MATERIALS

It was postulated that engineering plastics and composites may have been used in passenger vehicles because the price of the raw materials (i.e., of the resins and/or fibers) had decreased enough with respect to steel prices in the years preceding the adoption of these materials to directly affect the cost of an automotive component.

The historical price information for specific products (i.e. brand-name resins) currently used in automobile parts was requested from the suppliers of those resins was unavailable. In some cases, the customer service centers simply did not have the information; in other cases the producers were not at liberty to release the information.

Average list prices of some of the more common resins that have found application in automobiles were examined instead. Price data were obtained for the following generic resins:

- polyester,
- epoxy,
- PBT,

- polycarbonate,
- PPO-based, and
- amorphous nylon.

The data were obtained from Plastics Technology, which publishes monthly market price updates [64]. The resin prices as well as the price of steel are shown in Figure 7 on page 34 and Figure 8 on page 35. The figures show the price history of several materials in the years 1978 to 1986 in current dollars, and the same data normalized to 1984 constant dollars (using the indexes published in [70]) respectively. Note that although the graphs depict average market prices, they nevertheless show the general trend of stability in the price of plastics.

The trend was confirmed through direct interviews with plastics suppliers who indicated that indeed there had not been significant price fluctuations. From this evidence, it was concluded that the price of the raw materials did not influence the adoption of engineering plastics and composites into passenger vehicles.

4.2 LABOR RATES

Again, data on labor rates reflect average hourly wages, as supplied by the Department of Labor of the U.S. Government [70]. Figure 9 on page 37 shows labor rates in the United States for the years 1977 to 1984, in current dollars, as well as normalized to 1984 constant dollars. Because it is apparent that labor wages were stable, it was concluded that the price of

Neat resin prices

In dollars of that year

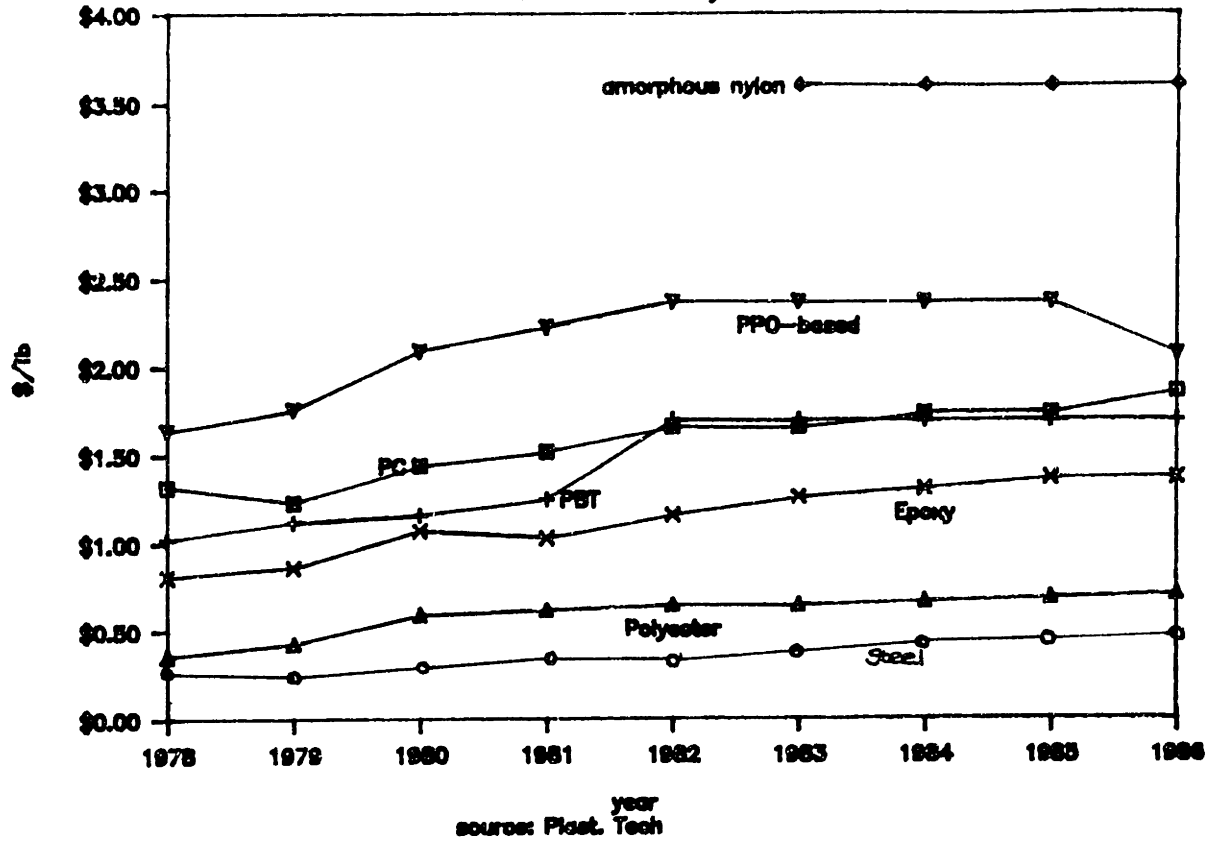


Figure 7. Price history of selected commercial resins (current dollars)

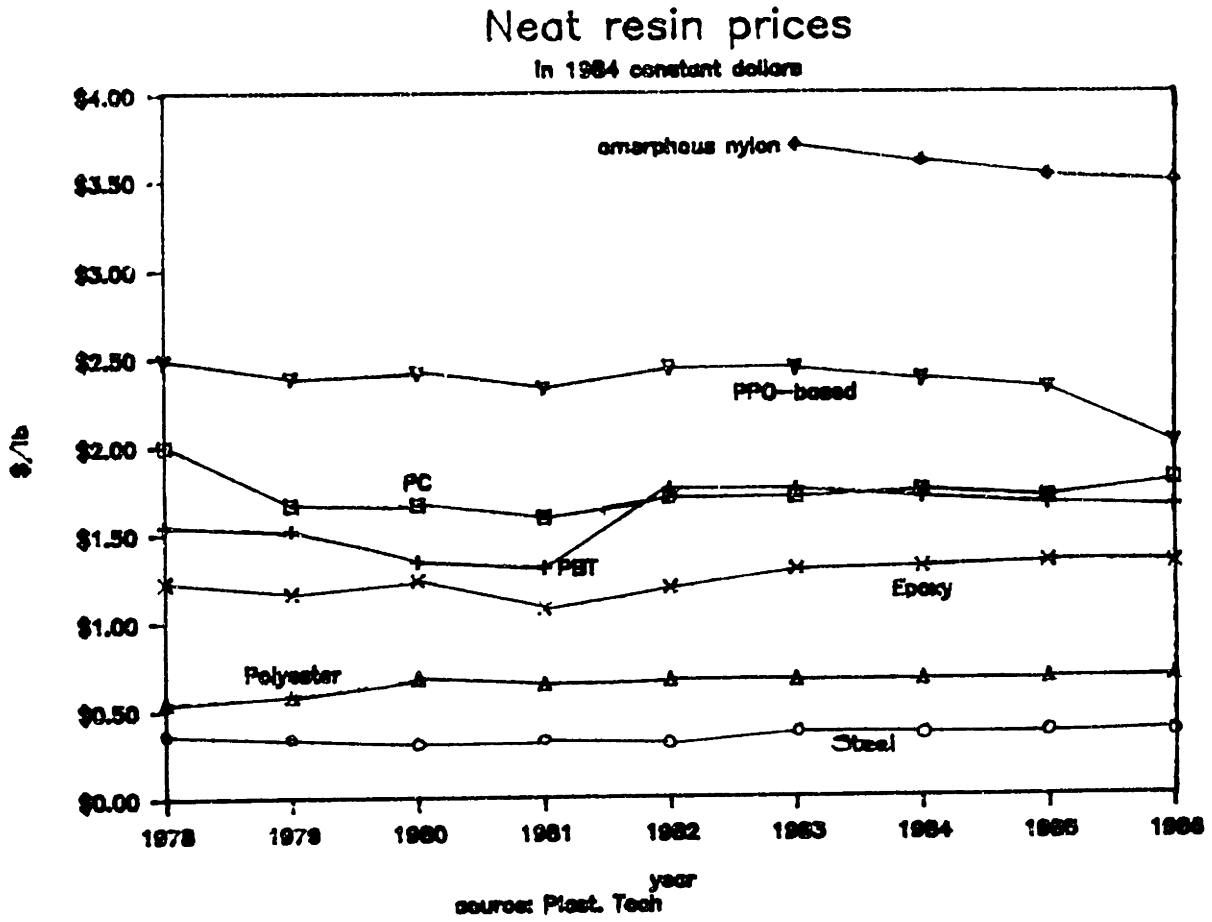


Figure 8. Price history of selected commercial resins (constant dollars)

labor did not trigger the increase in consumption of engineering plastics and composites.

In conclusion, neither the price of raw materials nor the cost of labor, appear to have effected the sudden increase in consumption of engineering plastics and composites in automobiles.

Average hourly earnings

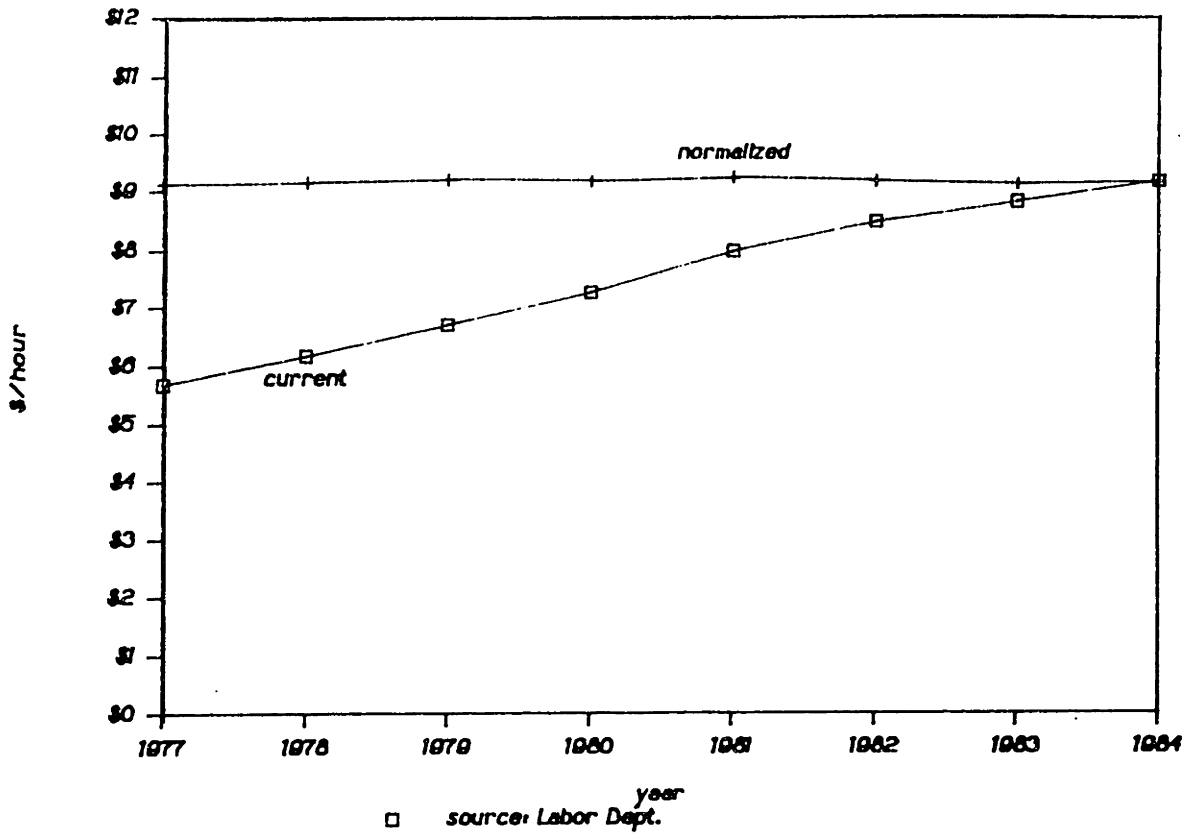


Figure 9. Trend in U.S. labor rates

5. TECHNOLOGICAL INNOVATIONS

Technological innovations were found in each of the cases studied, and it was therefore postulated that a correlation existed between the consumption of engineering plastics and composites and technological change as discussed in Chapter 3.

For each case study, key materials and/or process innovations were explored. Materials innovations were defined as either the development of a new monomer, or of a material with different capabilities from what was previously available.

Process innovations were defined as the invention or development of a new process, or the modification of an existing process. However, materials and process innovations often were inter-related, as a materials development can force a process change and vice versa.

Investigation into the case studies involved interviews with researchers and developers of the selected components. A summary of key innovations is shown in Table 3.

TABLE 3 - SUMMARY OF INNOVATIONS

PROJECT	KEY INNOVATIONS
driveshaft	PROCESS INNOVATION - Translating mandrel
transverse leaf spring	PROCESS INNOVATION - winding multiple springs into a cavity
longitudinal leaf spring	PROCESS INNOVATION - winding multiple springs into a cavity
all-thermopl. bumper	MATERIAL INNOVATION - all plastic system made with a blend
thermoplastic composite bumper beam	MATERIAL INNOVATION - thermoplastic reinforced with continuous glass fibers
composite hood	MATERIAL/PROCESS INNOVATION - faster cycle time, in-mold coating
thermoplastic vertical body panel	MATERIAL INNOVATION - polymer blend
RIM body panel	MATERIAL/PROCESS INNOVATION - shorter cycle times and internal mold release
amorph. nylon rear quarter panel	MATERIAL INNOVATION - polymer blend
composite tailgate	MATERIAL/PROCESS INNOVATION - faster cycle time, in-mold coating
thermoplastic composite load floor	MATERIAL INNOVATION - thermoplastic reinforced with continuous glass fibers

Table 4 presents some additional information on the sample. In most cases, the materials suppliers bore the cost of innovating but they did not produce the components: they simply supplied material to their clients. It was found that all innovations were targeted towards meeting performance requirements (where performance refers to physical, mechanical, and environmental characteristics, not previously necessary or attainable at a competitive cost. Additionally, the majority of the innovations were targeted specifically to the automotive industry. However, it was also found that the innovations could have been done earlier, as indicated by similar projects having occurred elsewhere and/or earlier. Information about the evolution of the innovative applications studied in this research is summarized in Table 5. The Table indicates that the materials suppliers were not technologically incapable of developing the innovations at a different point in time.

TABLE 4 - INNOVATION DATA

CASE	INNOVATION COST BORNE BY ...	INNOVATION COST-COMPETITIVE WITH STEEL	INNOVATOR MANUFACTURES COMPONENT
composite driveshaft	materials supplier	yes	yes
transverse leaf spring	automotive company	yes	yes
longitudinal leaf spring	automotive company	yes	yes
all-thermopl. bumper system	materials supplier	yes	no
thermoplastic composite bumper beam	materials supplier	yes	no
composite hood	materials supplier	yes	no
thermoplastic vertical body panel	materials supplier	yes	no
RIM body panel	materials supplier	yes	no
amorph. nylon rear quarter panel	materials supplier	yes	no
composite tailgate	materials supplier	yes	no
thermoplastic composite load floor	materials supplier	yes	no

Key technical variables (associated with the process and/or product) were identified and studied over the past several years. The effect on piece cost of a change in technology was explored. Using technical process cost models (details on cost modeling can be found in Appendix C), cost analyses were generated for various processing conditions.

Details on each component are presented in Appendix A, but the key findings about each innovation are presented in the sections that follow. The criteria for innovating, the functional locus of the innovation (i.e., materials supplier, equipment manufacturer, automotive company, or custom molder), and cost analyses associated with technological change are discussed. The sections that follow are divided by category of innovation.

5.1 PROCESS INNOVATIONS

The cases presented here, composite leaf springs and driveshafts, are examples of process innovations in which an existing, traditionally non-automotive process was extensively modified to meet the high production volumes required by the automotive industry. In all cases, the composite components had to outperform their metal counterparts cost-effectively.

5.1.1 LEAF SPRINGS

TABLE 5 - EVOLUTION OF THE INNOVATIVE APPLICATIONS

CASE	INNOVATION COST BORNE BY ...	SIMILAR APPL. IN OTHER COUNTRY	SIMILAR INNOV. IN NON-AUTO. APPLICATION	INNOVATION POSSIBLE EARLIER
composite driveshaft	materials supplier	no	yes	yes
transverse leaf spring	automotive company	no	no	yes
longitudinal leaf spring	automotive company	no	no	yes
all-thermopl. bumper system	materials supplier	yes	no	yes
thermoplastic composite bumper beam	materials supplier	no	yes	yes
composite hood	materials supplier	yes	no	yes
thermoplastic vertical body panel	materials supplier	no	no	yes
RIM body panel	materials supplier	yes	no	yes
amorph. nylon rear quarter panel	materials supplier	no	no	yes
composite tailgate	materials supplier	yes	no	yes
thermoplastic composite load floor	materials supplier	no	yes	yes

Composite leaf springs, both transverse and longitudinal, are made of an epoxy matrix, reinforced with continuous glass fibers. The process used to produce them is filament winding, followed by compression molding. The locus of the innovation in this case was the automotive company. The process is highly proprietary, such that few specific details are available.

However, some published literature on the development of composite leaf springs [9, 16, 34, 36, 41] suggests that an innovative form of filament winding is used, which allows for the simultaneous production of multiple springs. Additionally, even the design of the new springs is innovative: a ten-leaf steel spring was replaced by a one leaf composite spring, weighing 1/5th as much. A comparison of the key performance characteristics of a steel versus a composite spring is shown in Table 6.

TABLE 6 - ENGINEERING PARAMETERS OF A STEEL AND A COMPOSITE LEAF SPRING

CHARACTERISTIC	CORVETTE COMPOSITE TRANSVERSE SPRING	CORVETTE STEEL SPRING
weight	3.6	18.6
number of leaves	1	10
modulus of elasticity (MPa)	37400	200000
elongation	5.00%	0.50%
design stress (MPa)	586	758
elastic strain energy (Nmm/kg)	2358	173
corrosive	no	yes
strength/mass ratio (relative)	5	1
fatigue life (relative)	5	1

Filament winding had traditionally been a low-volume production process. In order to meet the production targets of the automotive industry (40,000 leaf springs per year initially for the Corvette, up to 80,000 per year for some Cadillac models), enormous capital expenditure would have been necessary if conventional process equipment had been used in parallel production lines. Instead, by extensive modification of a standard filament winder (of the W-60 type, as supplied by McClean-Anderson), the automotive production goals could be met, at a price competitive with the steel counterpart, i.e., on the order of 35-37 \$/spring.

The purpose of the leaf spring innovation was to improve the performance characteristics of the leaf spring at a price competitive with that of steel (i.e., by meeting the required production goals). It was particularly important to improve the fatigue life and corrosion resistance, and to reduce weight. The new mono-leaf design allowed for more design freedom by permitting a lower front-end design, all of this at a price in the same range as the part that was being substituted.

5.1.2 COMPOSITE DRIVESHAFT

Composite driveshafts were designed in the U.S. to replace 2-piece steel shafts in passenger vans. They are made of an epoxy matrix, reinforced with graphite and glass fibers, and they are filament wound. The traditional filament winding process was extensively modified to meet the high production volumes of the automotive industry.

The process innovation was a filament winder with a translating mandrel that could wind shafts continuously. Thus, the production targets for automotive applications (initially 30,000 shafts/year) could be met at a cost competitive with that of steel. A steel shaft costs on the order of \$80, whereas a composite one costs about \$90 [2, 19, 25].

Because composite driveshafts are one-piece, they have lower assembly costs than the 2-piece steel counterpart. Composite driveshaft one-piece assemblies offered noise reduction because of less vibration.

The innovation cost for composite driveshafts was borne entirely by the materials suppliers (the initial development work was done by a producer of carbon fibers). There was some participation by the equipment manufacturer (i.e., the manufacturer of the winder), but the expenditure was all on the part of the materials supplier. The supplier intended to sell a finished component to the automotive company. Details of the development program may be found in Appendix A.

At the present time, U.S. vehicles do not use composite driveshafts, due to problems with the entire power train assembly. This is an interesting case of a bad approach taken by a supplier, and is referred to again later to illustrate the type of approach that a supplier should avoid.

The purpose of this innovation was, again, to improve performance characteristics at a cost competitive with the 2-piece steel shaft.

5.2 MATERIALS INNOVATIONS

This section discusses innovations in thermoplastic materials that were necessary to make them acceptable for use in automotive applications. Several engineering parameters had to be satisfied and, as in all other cases, this had to be done at a cost that was competitive with steel (the traditional material).

Although estimates of the exact cost of an exterior panel are unlikely to be exact because of the many variables which interact in the production of a component, inter-material comparisons can be made that give reasonable estimates. It is especially relevant, when studying plastics and metals, to compare materials and capital equipment costs. With plastics, the materials cost is high and the capital cost is low; with metals, the reverse is true. Therefore, at lower production volumes, as is becoming more common², plastics become more cost effective (provided they can meet the required performance characteristics).

5.2.1 ALL-THERMOPLASTIC BUMPER SYSTEM

The Ford bumper system found on Taurus, Sable and Aerostar vehicles made by Ford, is the first to be made entirely with thermoplastic material in the

² There is an increasing tendency to change the exterior styling of an automobile often, while maintaining the same platform. Therefore, the production run of an exterior component is smaller.

United States. This system is innovative in both design and materials usage.

The material supplier (General Electric, Plastics Division) entirely funded its development which required a new design as well as a new material. The bumper material is an alloy of polycarbonate (PC) and polybutylene terephthalate (PBT), and can be formed using standard injection molding. A similar development had taken place in Europe previously [24, 27].

Although the performance requirements were not identical, the approach taken to develop the necessary materials was comparable, indicating that an all-thermoplastic bumper system was technologically and economically feasible.

The material was created specifically to meet the performance requirements for this application, with special emphasis on improvements over steel in corrosion resistance, weight and cost. In the U.S., the bumper system had to withstand 5 mph impacts, as dictated by the Federal Motor Vehicle Safety Standard (FMVSS) and the automotive company's voluntary internal standard; in Europe, on the other hand, where the first all-thermoplastic bumper system was employed, the safety standard is for a 2.5 mph. impact.

5.2.2 THERMOPLASTIC BODY PANEL

Advanced thermoplastic materials are used for vertical body panels such as the rear quarter panel on the Pontiac Fiero, and are being developed for door panels. The quarter panel on the Fiero is made with Bexloy C, an

amorphous nylon blended with a proprietary additive. General Electric's GTX resin has also been developed for use in automotive body panels.

Although the material was developed specifically for the rear quarter application, it was injection molded using conventional technology. The design for the panel was done as a co-operative effort between the material supplier and the automotive company.

The material was intended specifically for exterior body applications, to meet performance requirements such as improved corrosion resistance over steel, as well as class-A surface³. Current thermoplastic body panel applications are painted off-line; they do not have to withstand the 350 degrees F paint ovens where steel parts are normally painted.

Using a plastic panel rather than a steel one achieves more design flexibility at a lower cost. Effectively, the product (i.e., the panel) has a short manufacturing lifetime, and investments in new tooling are needed to change the external appearance of the car. A cost analysis was performed which compared the fabrication of a steel panel to an equivalent (dimensionally and performance-wise) thermoplastic panel, as a function of annual production volume using scenarios for product lifetime of one and two years. The results of the analysis are shown in Figure 10 on page 51, where dedicated equipment was assumed. The details of the assumptions used

³ Class A is a term used in automotive engineering to describe the appearance of the surface of a panel. Class A must be obtained before a product can be used in exterior (visible) body paneling.

in the cost estimates can be found in Appendix C. Figure 10 on page 51 shows the trend for injection molding to be less costly for production volumes up to 180,000-200,000 panels per year. Steel is less costly above 200,000 panels per year, for a production run of 1 or 2 years. Thus, for vehicles whose exterior appearance is modified frequently, thermoplastic materials seem economically advantageous.

5.2.3 THERMOPLASTIC COMPOSITE BUMPER BEAM AND LOAD FLOOR

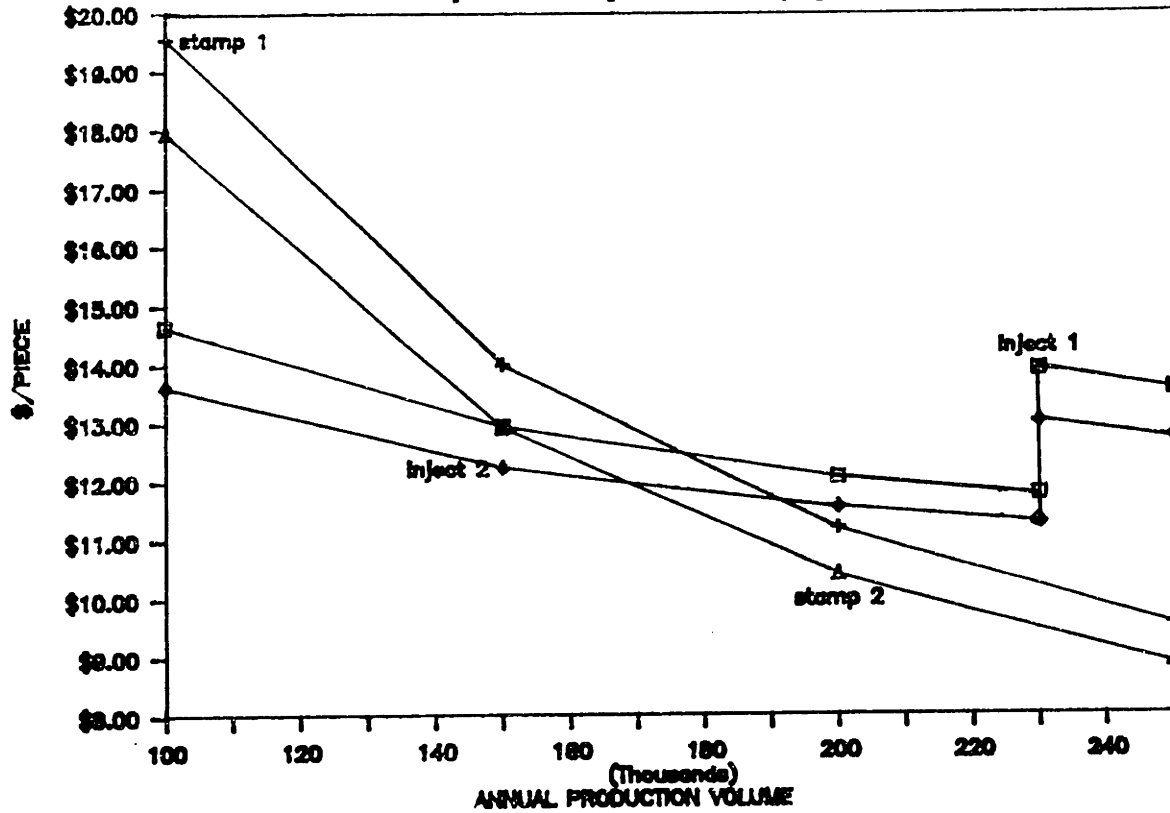
Thermoplastic materials reinforced with continuous glass fibers are currently used in a variety of applications. In the automotive structural area, glass-reinforced polypropylene laminate is used in load floors and in bumper beams. The parts are produced using high-speed thermoplastic stamping, and are then electromagnetically bonded.

The innovation in structural automotive applications is the use of continuously reinforced thermoplastic composites, fabricated with a high-speed process. Although the material was not developed specifically for the automotive market, it was used structurally in the automobile beginning in 1985.

To summarize, the materials innovations discussed in this section led to applications where they performed better than their metal counterpart. In the bumper system case and the thermoplastic composite case, the technology was proven elsewhere (in Europe and in other applications) before being used in the U.S.

PIECE COST OF AN AUTOMOTIVE PANEL

Injection molding vs. steel stamping



Assumptions:

- stamp 1 - steel panel, 1 year product lifetime
- stamp 2 - steel panel, 2 years product lifetime
- inject 1 - plastic panel, 1 year product lifetime
- inject 2 - plastic panel, 2 years product lifetime

Figure 10. Costs of a panel as a function of volume and length of production run.

5.3 MATERIAL/PROCESS INNOVATIONS

This section discusses those innovative plastic applications where changes in the material and the technology went hand-in-hand. SMC (sheet molding compound) and RIM (reaction injection molding) were investigated. The locus of the innovations was again the suppliers.

SMC and RIM materials processing are currently used for exterior appearance parts, i.e., for body panels, substituting steel.

A comparative cost analysis was performed to examine the effect of technological change on the cost of the part. The estimates show whether a correlation existed between a change in cost (as influenced by innovations in the technology) and an increase in the use of the material/process.

The estimates used computerized processing cost models for plastics molding and for steel stamping. The models are based on a series of technical variables, such as scrap rates, which were input according to the status of the technology each year. Each shaded area represents an uncertainty band of +/- 20% from the estimated cost, which is the degree of accuracy to be expected from an estimate.⁴

⁴ The models are based on a series of inputs which are average values, therefore not reflecting the costs of any one particular manufacturing facility. Thus a confidence interval is more appropriate here than a single value. See Appendix C for more details.

The fender for a small vehicle was selected to compare processing costs over time, as a function of the changing technology (the engineering parameters, including part dimensions, were supplied by an auto manufacturer). Estimates were made for producing it out of stamped steel, SMC, and RIM in the same annual volume of 100,000 units.

The cost of a stamped steel fender was used as the baseline. Steel stamping technology has not changed significantly over the past 30 years. In automotive applications, however, the material has been changed to galvanized steel, which is more expensive. Additionally, the time to change the die has dropped from 4 hours to 2 hours, decreasing the cost of a panel made out of steel.

5.3.1 RIM BODY PANEL

The current, most common, RIM⁵ material is polyurethane, and polyurea material is also appropriate for RIM processing.

Two of the most significant innovations in RIM were the invention of internal mold release (IMR) and developments in the chemistry of the polyurethane materials. The material available in the mid-1970's had turbulent viscosity which caused air entrapment; it consequently exhibited poor surface quality, high reject rates and required long cycle times to

⁵ RIM, reaction injection molding, often denotes both the material and the fabrication process.

obtain components with an acceptable surface. The innovations reduced cycle time from 7 minutes in 1975 to 90 seconds in 1984, and decreased the reject rate from 16% to 6%.

A short cycle time is imperative to meet production goals cost-effectively. The longer cycle time effectively increases the cost of each molded part, by requiring higher capital and labor investments.

The introduction of amine chain extenders decreased the cycle time and improved the surface quality of the part. This improvement was taken a step further by developing an internal mold release (IMR) product which increased molding productivity by eliminating the need to spray the mold with release before molding each part. Using the IMR material, 50 parts could be molded without cleaning the mold.

Figure 11 on page 55 shows the results of the comparative cost estimates of a steel and RIM fender for the period 1975-1984. The estimates show that the innovations in RIM made it cost competitive with steel only in recent years.

5.3.2 SMC HORIZONTAL BODY PANEL AND TAILGATE

Innovations in SMC molding were explored using the same framework as RIM. The scrap rate during SMC processing has decreased from 12% to 0.5%, through incremental process improvements. Cycle time, a key variable in automotive plastics processing, is expected to decrease from 120 seconds

PIECE COST

small fender

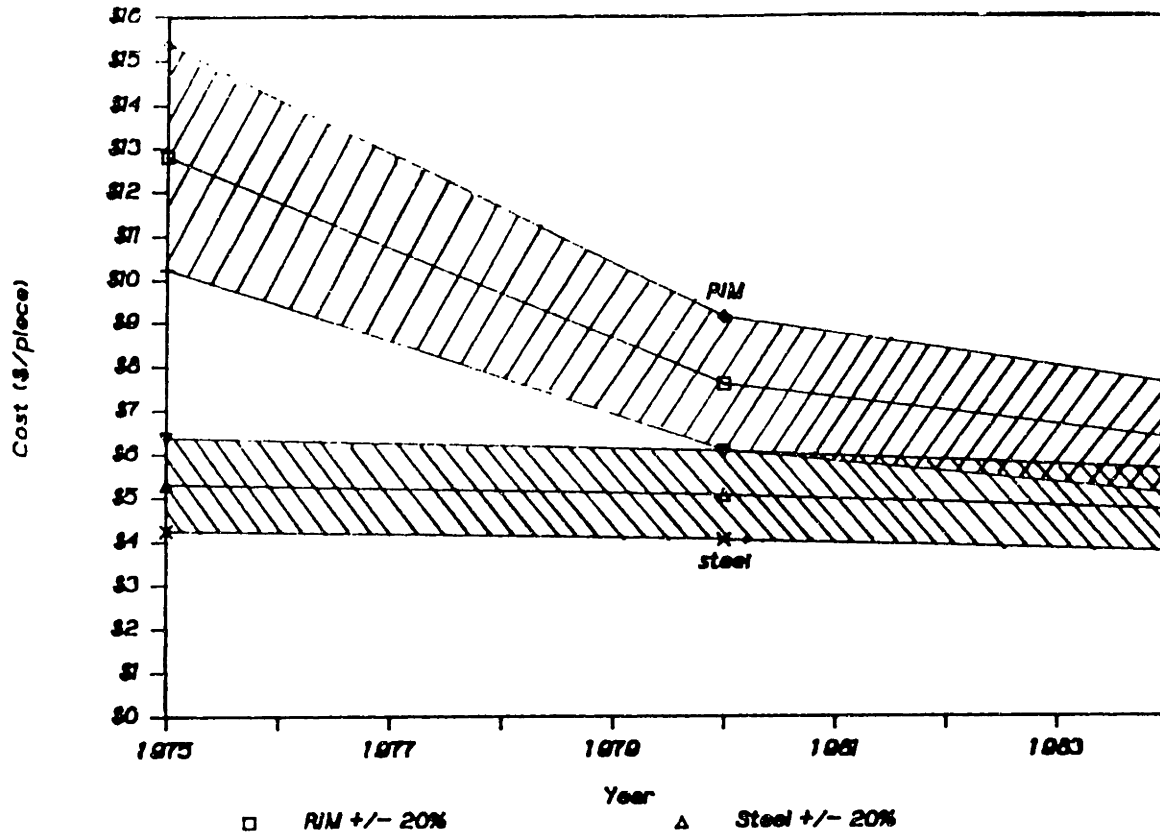


Figure 11. Piece cost of a RIM part over time as a function of technological change

(on average currently) to 60 seconds by 1989. A key innovation in SMC is the successful introduction of in-mold coating. In-mold coating improves the surface quality of the body panel.

The piece cost of an in-mold coated part is higher than a part that does not undergo this treatment, because the cycle time is increased by 30 seconds. However, the overall system cost (i.e., the cost of the assembled vehicle) is reduced.

The cost of an SMC fender, as a function of the technology, was estimated for the period 1975-1989. The results of the estimate are shown in Figure 12 on page 57 where the steel equivalent is also displayed for comparison purposes. The cost of SMC dropped due to the decrease in scrap rate and the projected decrease in cycle time as discussed above. The evidence leads to a conclusion that innovations in SMC have not decreased piece cost, and that the technology was not holding back the application of SMC. SMC is considered the least innovative of all the applications. The market for SMC is in fact fairly saturated, pointing to the fact that technological innovations were not necessarily a cause for materials substitution.

To summarize, the innovative applications which led to developments in materials/processes were targeted towards making the new part economically. However, the cases of RIM and SMC were not novel, in that they had been used in other types of less demanding applications, such as bumper fascias and truck panels respectively. Once again, other reasons than a lack of

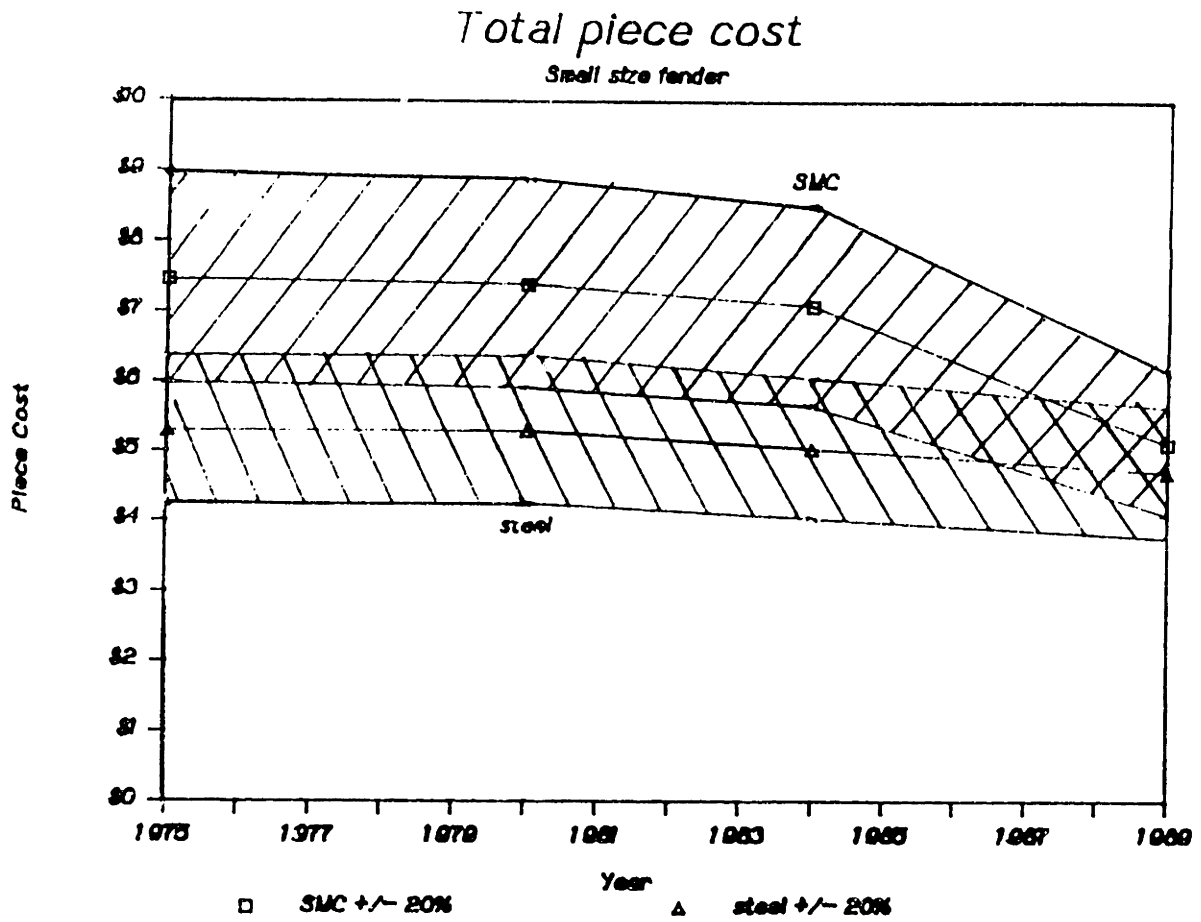


Figure 12. Piece cost of an SMC part over time as a function of technological change.

technology prevented the use of plastic materials in structurally demanding applications in automobiles.

5.4 PURPOSE OF THE INNOVATION

All the technological innovations studied decreased the cost of the new component as compared to the metal component that was being replaced (if not on the basis of a single component, at least on the basis of the overall system). It was also found that in the majority of the cases, improvements in the performance of the component were obtained through innovation.

It also appears that the cases which have undergone the least innovation, i.e., SMC, are approaching market saturation.

The materials supplier was the innovator in all cases except that of composite leaf springs. "Innovator" is defined as the functional group (manufacturer, supplier, or automotive company) which took the risk, i.e., bore the cost, of developing materials and/or processes such that they could be used in the automotive industry. The suppliers of materials to the automotive companies were more willing than other groups which operate within the automotive industry to invest considerable resources to innovate. Neither custom molders nor equipment manufacturers were found to be innovators.

Table 5, shows that a lack of technology had not held back the majority of the innovative applications of engineering plastics and composites in demanding automotive areas. On the contrary, in some cases, the technology

was available two decades ago but was not utilized on a commercial scale (leaf springs and driveshafts). The availability of technology was measured in two ways: 1) by examining whether the materials and/or processes were used in non-automotive applications, and 2) whether a similar technology had been used in other countries. Consequently, other forces must have been acting on the automotive industry. What caused the innovations and what led the materials suppliers to commit resources to innovating, as a functional group, is the topic of the next chapter.

6. CAUSES OF INNOVATION

This chapter investigates the factors which caused the innovations in plastics and composites used in automobiles. The chapter is divided into two main sections, on the basis of the research chronology. The first section discusses the preliminary collection of data through interviews. Information gathered in this initial stage of research was used to generate hypotheses (i.e., possible explanations) to explain the innovations. The hypotheses, and their verification are discussed in the second section of this Chapter.

In general, the innovative applications of plastics and composites in automobiles discussed in the previous chapter, were stimulated by the perceived need for materials, processes and components with the characteristics exhibited by the new developments. It was found that in the majority of cases studied, the locus of the innovation was the materials supplier (refer to Table 4). The locus of innovation is defined as the functional group (supplier of the material to make the plastic or composite component, manufacturer of the component or user of the component) which took the risk i.e., funded the innovation.

Innovation requires a large commitment of time and funds with the expectation of a sizeable reward from the innovation. Since in the majority of cases the innovations were done by materials suppliers, the driving force that drove them to innovate was investigated. Two fundamental questions arose here: 1) what prompted the supplier to bear the cost of innovating?

and 2) why the interest in plastics in the late 1970's and not before or after?

It was found that the only reason materials suppliers innovated was to increase profits. It also appeared that the suppliers innovated in response to a perceived demand for the innovation. Other reasons for innovating that were initially postulated, such as the ability to utilize existing resources, or the commitment from the auto company of a long supply contract, were considered "desirable conditions" but were not driving the innovations, according to the individuals interviewed.

6.1 DATA COLLECTION

The preliminary data were gathered from interviews done in two stages. From these interviews, a number of conclusions were reached about industry-wide trends in the adoption of advanced polymeric materials in the automotive industry. The information gathered during this stage was used to formulate hypotheses about the causes for supplier innovation. Questions were then asked to industry experts to prove or disprove the hypotheses.

6.1.1 INTERVIEWS

Exploratory interviews were followed up by specific interviews following a questionnaire format. People from many types of companies, i.e., materials suppliers, molders, automotive companies, and equipment manufacturers, with

engineering as well as marketing roles, were interviewed in the exploratory stage, and the interviews included general discussions about the approach taken by suppliers to select the direction of their research and development (R&D) efforts. These interviews generated a series of postulates to explain: 1) the observed increase in consumption of advanced polymers and 2) supplier involvement in R&D. The postulates were subsequently verified using a questionnaire-type format.

The people interviewed and their company affiliation are listed in Appendix D. Details of the single interviews are not listed, as many people preferred to keep the information confidential. The materials suppliers whose products are in use today were interviewed for the second stage of the research. The interviewees were people with marketing roles, from companies that supply material for the components in the sample of case studies.

It was decided to conduct discussions over the telephone, and not to mail out questionnaires both because of the rather limited size of the sample (as expressed by the number of cases studies), and to ensure a high response rate. Personal conversations tend to stimulate discussions that offer more insight than a written questionnaire.

6.1.2 OBSERVED AUTOMOTIVE INDUSTRY TRENDS

The exploratory research showed a number of automotive industry trends as expressed by suppliers, custom molders, makers of molding equipment and the automotive companies. The trends discussed below are not generalizations

of industry-wide rules: they are relevant topics with regard to the substitution of plastics for traditional materials. The trends were used to generate hypotheses and to formulate questions about the observed industry behavior.

LOCUS OF THE INNOVATION

As mentioned in Chapter 5, the innovations were performed largely by the materials suppliers. The equipment manufacturers (see Appendix D) indicated that they modify their equipment in response to specific requests by their customers, but they don't consider themselves to be an innovative group. Likewise, the custom molders tend not to take on risky activities such as developing new materials. This is to be expected, because the locus of the innovation is where the maximum benefit is to be found [44]. Both the molders and the manufacturers of equipment have a well established market, often operating at or near capacity, and therefore do not have the incentive to innovate.

CONTRACTUAL AGREEMENTS

There was recurring mention of sales agreements between suppliers and their customers being too short (the standard contract is usually one year [59]). An innovative supplier thus has no way of protecting himself from being replaced by a lower cost bidder, who had not borne the cost of innovating.

In 1979, the friction between the automotive firms and their suppliers led to some two- and three-year contracts being negotiated [59]. Longer contractual agreements for the supply of a material and/or a component were thought to enhance supplier involvement in the innovation process.

Both the materials suppliers and the automotive companies interviewed indicated a need for more supplier involvement, partly because the automotive companies lack experience with non-metallic materials and are reluctant to get involved, and partly to shift the cost of the innovations to the suppliers. The suppliers accept such a burden because of the potentially large profit.

REGULATION

The introduction of the CAFE (corporate average fuel economy) regulations was mentioned as another promoter of materials substitution. These regulations were introduced in 1975, became effective in 1978, and were intended to force automotive manufacturers to improve the fuel economy of their cars [31, 68]. Initially, the regulation reduced vehicle weight in every possible way, and promoted the use of lower density materials, such as plastics, aluminum, magnesium and ceramics.

Only in the first year following introduction of governmental regulations were the automotive companies willing to pay a price premium in order to reduce vehicle weight, which consequently improved fuel economy. In the 1980's, on the other hand, both the suppliers and the auto companies, per-

ceived that the innovative component had to be cost competitive over time with the part that was being substituted.

INNOVATION TOWARDS HIGHER VALUE-ADDED OR LOWER DEVELOPMENT COSTS

Materials innovations consisted mostly of developing new polymer alloys. Polymer alloys are mixtures of two or more resins blended, usually in the molten state, to form a new material. Individual polymer segments are intimately mixed (for example by hydrogen bonding) but no chemical synthesis or formation of new covalent bonds occurs [47].

This type of alloying effort diverges from the more traditional ways of innovating with polymer materials, such as the development of new molecules or new molecular weight grades, or the modification of properties by changing molecular weight distribution. The growing activity among materials suppliers is to take off-the-shelf resins and put them together in new ways to create a synergism yielding properties that were not available before. This concept has been implemented for some years, but previously on a much smaller scale. Now, the effort is more sophisticated and intensified because plastics have reached a more positive degree of acceptance. The sophistication of automotive plastic materials users, and their desire to offer innovative and cost-effective designs in an increasingly competitive market place, is driving current alloying and blending activities [47, 69]. Successful cases of polymer alloying activity are: General Electric's Xenoy material, a blend of polycarbonate and polybutylene terephthalate;

and DuPont's Bexloy C, a blend of amorphous nylon and a proprietary toughener.

Polymer alloys are seen as a cost-effective way for the supplier to create a new product by utilizing materials already produced. Expertise with the starting materials, as well as already existing production facilities can lead to supplier innovation in order to utilize existing resources.

Some materials suppliers mentioned an interest in selling finished components to join the higher value-added market. In the cases studied, with the exception of driveshafts, the suppliers only supplied the material, and not a finished component.

JOINT VENTURES

Joint ventures, such as the formation of the company Azdel, between PPG and General Electric [52], can also be considered a route to utilize existing resources. Azdel currently produces a thermoplastic composite, reinforced with continuous glass fibers. This joint venture combines the expertise in composites of PPG, with the expertise and production facilities in thermoplastic resins of G.E.. Azdel successfully markets a product with higher-value added, thus offering the potential for greater profit.

SUMMARY OF AUTOMOTIVE MATERIALS INDUSTRY TRENDS

The salient points about plastics materials and the automotive industry were gathered through preliminary interviews. These included: cost competitiveness of the innovation, materials supplier involvement, innovation towards higher value-added products, regulation, and contractual agreements. The information gathered regarding automotive plastics trends is used to formulate hypotheses to explain the use of advanced polymeric and composite materials in automotive structures.

6.2 HYPOTHESES REGARDING INNOVATION

Based on the preliminary research, five hypotheses were generated to explain the innovation behavior observed through the case studies (i.e., why materials suppliers tended to be the innovators in the auto industry, and the timing of their innovations).

The postulated explanations are:

1. Suppliers took the risks of innovating, as a means to increase sales and profits.
2. Because materials suppliers often had had expertise with materials comparable, (or constituent), to the innovations, it was postulated that they innovated because their expertise and production capacity were otherwise lying idle.

3. Many of the innovations yielded products with greater value-added e.g. driveshafts, TP composites, etc. Because higher value-added products offer a higher profit margin, it was postulated that suppliers innovated by offering those products.
4. Long supply contracts can be a means for reducing the risks of innovating for the supplier. If the supplier obtained such an agreement, it would innovate.
5. Suppliers innovate in response to a perceived need of their (potential) customers.

The five postulates listed above are referred to throughout this thesis as "hypotheses", and were formulated to be proved or disproved by direct questioning of the materials suppliers. Marketing personnel in materials supplier companies were asked if they innovated:

1. to increase sales and profits;
2. to utilize existing resources, both in terms of expertise and manufacturing capabilities;
3. because there was more value-added (and hence more profit-making potential) to be realized by innovating;
4. because they had obtained, or could obtain, a long supply contract; and

5. because they perceived that the automotive companies demanded such an innovation.

The questions solicited "yes" or "no" answers, in order to clearly separate the relevant hypotheses. The questions asked to verify the hypotheses and the answers obtained are listed in Table 7.

TABLE 7 - SUMMARY OF POSTULATED CAUSES OF INNOVATION

CASE	Did the supplier innovate ...				
	TO INCREASE SALES?	TO UTILIZE EXISTING RESOURCES?	BECAUSE OF VALUE ADDED?	BECAUSE OF SUPPLY CONTRACT?	RESPONDING TO NEED?
composite driveshaft	yes	no	yes	no	yes
all-thermopl. bumper system	yes	no	no	no	yes
thermoplastic composite bumper beam	yes	no	yes	no	yes
composite hood	yes	no	no	no	yes
thermoplastic vertical body panel	yes	no	no	no	yes
RIM body panel	yes	no	no	no	yes
amorph. nylon rear quarter panel	yes	no	no	no	yes
composite tailgate	yes	no	no	no	yes
thermoplastic composite load floor	yes	no	yes	no	yes
	(1)	(2)	(3)	(4)	(5)

The responses clearly point out that suppliers innovate in response to a perceived demand that will result in increased materials sales for the supplier. This can be seen in columns (1) and (5) of Table 7.

Hypotheses (2), utilizing existing resources, and (4), the existence of a supply contract, were not supported by the interviewees in any of the cases studied. Hypothesis (3), value-added, was supported in only three cases, and is rejected as a plausible explanation for supplier-funded innovation. The three unsupported hypotheses were described by the interviewees as "desirable situations" in terms of supplier strategy. The strategic implications of the findings described in this Section will be discussed in Chapter 7.

It became apparent from this latter set of interviews that the mechanism for innovation is the following: because of increasing market share being captured by foreign-made cars and, to a smaller extent, because of regulation, the U.S. automotive industry became more receptive to new technologies. One of these novel technologies (but not the only one) was the use of engineering plastics or composite materials in body panels and structural areas of vehicles.

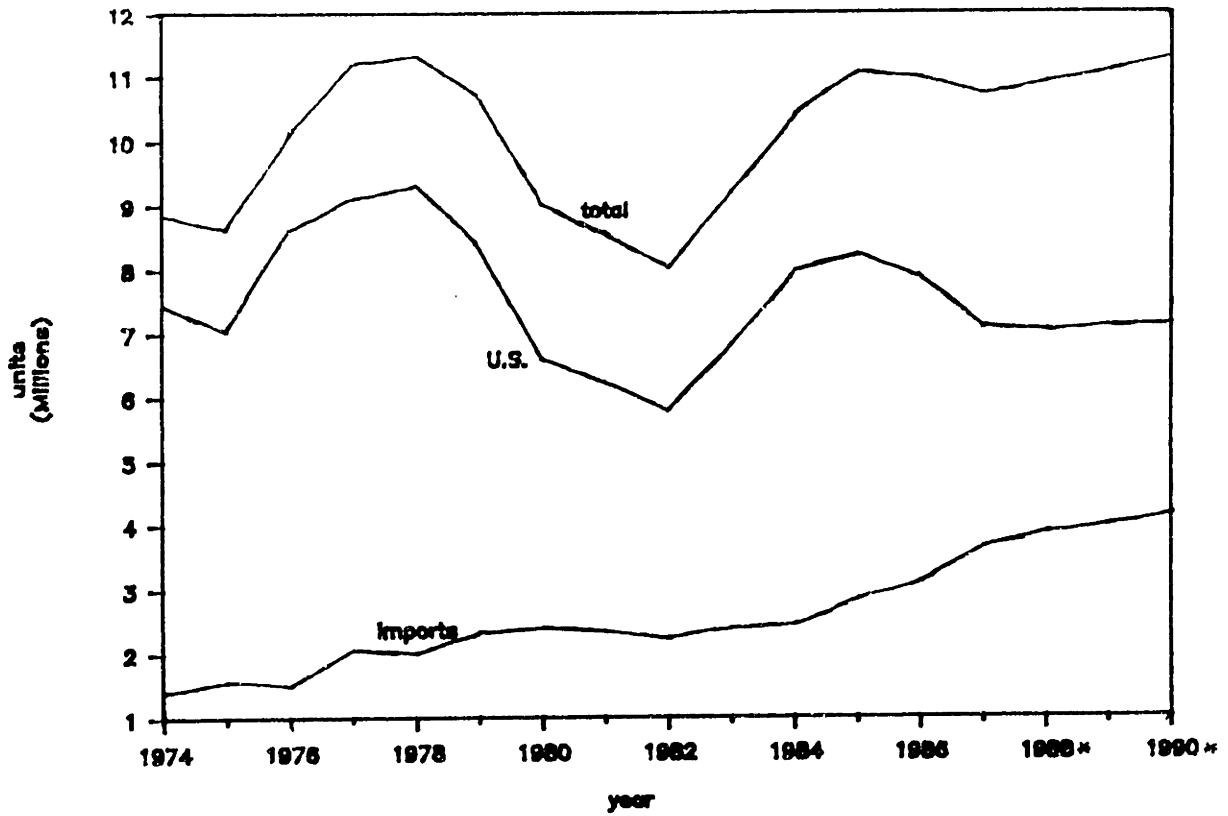
The materials suppliers perceived a change in attitude on the part of the automotive companies, resulting in a change in the demand for materials and processes to be used in structurally demanding areas. Due to the potentially large market size for the innovative materials/processes, the mate-

rials suppliers were willing to take on the burden of innovating. The causes of innovation will be discussed in the Sections that follow.

6.2.1 DECLINE IN SALES OF U.S. VEHICLES

Interviewees mentioned that the declining sales of U.S. vehicles was the primary reason U.S. companies considered plastics in structurally demanding applications in autos. Figure 13 on page 73 shows sales figures of domestic and imported vehicles in the U.S.A. [63]. The data clearly indicate a dramatic drop in sales of American-made vehicles from 1979 to 1982, whereas sales of imported cars rose slightly over the same period.

Sales of autos in the U.S.



source: Automotive News

Figure 13. Sales of automobiles in the U.S.A. (past and projected)

The drop in sales of American-made vehicles resulted from events in the world economy. To analyze of the global automotive industry is beyond the scope of this thesis, but a brief discussion about sales of automobiles in the U.S. can explain why plastics and composites became successful. In the 1970's, the operating environment of the world automotive industry changed radically as a result of the dramatic rise in the price of gasoline and subsequent concern over the use of fuel resources [1, 59]. Both the government and consumers demanded more fuel efficient vehicles that would be less costly to own and operate.

Because these nations historically have had limited fuel resources, foreign vehicles, i.e., European- and Japanese-produced, were already generally smaller and more fuel efficient than the American vehicles that were on the market in the 1970's. Foreign vehicles had a competitive advantage over American ones which they did not lose even during the economic recession of the latter half of the 1970's.

The loss of market share, shown in Figure 13 on page 73, prompted U.S. automakers to take a more lively interest in new technologies, including the use of plastics and composites. Although substituting plastics into cars is by no means the only way to improve the competitive position of an auto company, polymer technology was relatively advanced and could help the fuel economy problem at the same time. At the same time, U.S. auto manufacturers were investigating the use of aluminum to replace steel. Other technologies that were being explored to make U.S. vehicles more competitive, included sophisticated electronics to increase engine efficiency,

and changes in the aerodynamic design of the car to make them more fuel efficient. These technologies are beyond the scope of this thesis, but more details can be found elsewhere [15, 35, 37, 53, 54, 55, 56, 57, 58, 59, 60, 61].

6.2.2 PERCEIVED NEED

The perception of new technology as a means to curb loss of market share created a demand for innovations in products and processes. The demand manifested itself in a new receptiveness on the part of the automotive firms to new materials (i.e., non-metallic materials), and prompted materials suppliers to play an active role in the innovation process. Advanced polymeric materials are not the first case of supplier-funded innovation for the automotive industry: a well documented case of supplier-funded innovation is the aluminum trailers a materials supplier developed with the only incentive being the potential increase in aluminum sales [8, 42, 45].

This research attempted to measure the perceived demand. Demand can be expressed as a "wish list" of materials/process characteristics issued by the R&D department of an automotive company, which the suppliers respond to by making a product that follows the guidelines of the "wish list".

The timing of "wish lists" differs from product specifications. A product specification is a contractual definition generally issued after a material has already been selected for use in a production component. A "wish list", on the other hand, is an informal way to solicit from materials sup-

pliers their inputs to R&D programs. This is not the automotive company's officially approved methodology to spur innovation, but rather an intelligent approach taken by some engineers to solicit supplier involvement from the start of the concept.

A "wish list", or equivalent, may look something like Table 8. Because the list shown in Table 8 is taken from a proprietary document, critical values for the engineering parameters are not entered.

"Wishlists" are not a formal approach to solicit suppliers. Therefore, it was not possible to collect records of how they might have changed over time, indicating a shift in preference towards the properties of advanced polymeric materials. Additionally, they cannot be published, or they would expose future plans of the automotive company, possibly compromising its competitive edge. However, interested materials suppliers do have access to these lists, and it is therefore possible for them to monitor "perceived demand".

It was found that it is essential for a materials supplier to comprehend the requirements of the "wish list" or equivalent, in order to innovate successfully. The composite driveshafts (refer to Appendix A), is an example of a materials supplier who had a good idea for process innovation in principle, but who did not seem to understand the constraints of making a product for the automotive industry. Although one case is not conclusive evidence, it points to the fact that a misunderstanding of what is required may lead to devastating consequences.

TABLE 8 - EXAMPLE OF A WISH LIST FOR CHARACTERISTICS OF THE RESIN PORTION OF A COMPOSITE

GENERAL PHYSICAL PROPERTY REQUIREMENTS

Flexural modulus of neat resin	_____	psi or greater
Flexural modulus of composite	_____	psi or greater
Tough resin		
Low shrinkage	_____	% or less
Compatibility with standard fillers		

GENERAL PROCESSING REQUIREMENTS

Utilize standard equipment where possible		
Low viscosity		
Injection rates	_____	lbs/sec
Overall molding time	_____	1 minute or less

6.2.3 SUPPLIER INVOLVEMENT WITH THE AUTO INDUSTRY

This Section is intended to show that the suppliers' prior involvement with the automotive companies could have facilitated innovating towards their customers' needs. The materials suppliers examined in this research (with the exception of the drive-shaft manufacturer) had successfully supplied the automotive industry in the past with materials for other applications, as illustrated in Table 9 [53, 54, 55, 56, 57, 58, 59, 60, 61]. Prior working relationships facilitated co-operation with the automotive company, to better understand and meet their demands.

TABLE 9 - MATERIALS SUPPLIERS INVOLVEMENT WITH THE AUTO INDUSTRY

CASE	INVOLVED SUPPLIERS	PRIOR INVOLVEMENT WITH AUTOS?	SUCCESSFUL?
composite driveshaft	Hercules, Aerospace Div.	no	no
all-thermopl. bumper system	General Electric, Plastics Div.	yes - e.g. plastic headlamps	yes
thermoplastic composite bumper beam	PPG/Azdel, Inc.	yes - e.g. plastic retainers	yes
composite hood	Ashland	yes - e.g. truck panels	yes
thermoplastic vertical body panel	General Electric, Plastics Div.	yes - e.g. plastic headlamps	yes
RIM body panel	Dow Chemical	yes - e.g. bumper fascias	yes
amorph. nylon rear quarter panel	E.I. DuPont de Nemours	yes - e.g. license plate pockets	yes
composite tailgate	Ashland Owens-Corning	yes - e.g. truck panels	yes
thermoplastic composite load floor	PPG/Azdel, Inc.	yes - e.g. plastic retainers	yes

6.2.4 POTENTIAL MARKET

This research showed that materials suppliers innovated because of the large potential market. Because the innovations were targeted towards a specific type of component, each successful application would result in a large volume of sales. For example, an average of 40 lbs. of Xenoy material is used in each Ford Taurus, Sable, and Aerostar vehicle. Approximately 600,000 units were built in 1986, resulting in sales of approximately 48 million dollars of this material.

Thermoplastic composite material, used in bumper beams and load floors of various vehicles, brought sales of at least 6.5 million dollars in 1986. Similarly, SMC material in body panels brought sales of at least 12.5 million dollars among the vehicles discussed in this thesis (Chapter 2).

6.3 SUMMARY

The information gathered from the preliminary interviews was used to generate hypotheses to explain why materials suppliers innovated, and why they innovated towards the end of the 1970's.

Testing the hypotheses showed that American automotive manufacturers became responsive to technological innovation in structural and semi-structural materials when sales of their cars plunged as a result of the energy crisis (while sales of imported cars did not).

The materials suppliers thus responded to the demand for new materials by innovating. Innovation was therefore an effect of the desire/need to use new materials, and not a cause of substitution.

The following chapter discusses the strategic implications of these findings.

7. STRATEGIC IMPLICATIONS TO MATERIALS SUPPLIERS

The last chapter demonstrated it was the general slump in the automotive industry in the late 1970's that caused the automotive companies to become receptive to new technologies.

In expectation of increased sales and profits, materials suppliers respond to the perceived wishes of the automotive companies. For example, suppliers of RIM and SMC materials, for vertical and horizontal panels respectively, developed their technology to meet surface quality and fast cycle time requirements. Thermoplastic composite laminates fulfilled the automotive companies' needs for weight reduction. Further, the innovations of the early 1980's could have been implemented earlier had there been a market for them, as is indicated by the development of all-plastic bumper systems for European vehicles, and the use of SMC material in trucks. These facts indicate that the automotive companies currently have the upper hand in dictating the direction of new technology.

The implications of these findings are discussed in the following sections which will focus on the significance of contractual agreements between suppliers and the automotive companies, the formation of joint ventures, and the strategic implications to the suppliers of innovating as a means to utilize existing resources and manufacturing facilities.

7.1 CONTRACTS BETWEEN SUPPLIERS AND MANUFACTURERS

Two types of contracts exist between the materials suppliers and their customers. Supply contracts are usually contracts drawn between the materials supplier and the part manufacturer⁶ which commit the part maker to buy material from the selected source for a specified period of time, provided the material continues to meet the specifications agreed upon. This time period generally ranges from 3 months to one year.

Materials suppliers would prefer to lengthen the contractual commitment up to 3-5 years, to encourage materials suppliers to take even more innovation burden upon themselves. By guaranteeing a minimum market size for a new material, the supplier has the incentive to invest resources in innovation with the expectation of getting a good return on the investment. For the automotive company, a longer contract guarantees price stability.

Conversely, a longer contract locks the supplier into a contract with inflexible conditions even though the operation may not continue to be profitable. As well, the automotive company is bound to purchase the contract material over new materials that may become available during the period of the supply contract.

Longer supply contracts effectively discourage competition between suppliers, and, consequently discourages materials innovation, and is therefore disadvantageous to both the supplier and the automotive manufacturer.

⁶ The part manufacturer can be a custom molder, or a molding division of an automotive company.

Striving for a long supply contract is not competitively advantageous for the materials supplier, because of the risk of the agreement becoming unprofitable.

Recently, a "development agreement" between the materials supplier and the automotive manufacturer has been used. This agreement essentially states that the materials supplier will finance some of the costs of prototyping, designing and testing the new part (i.e., the part made with the new plastic material). In return, the automotive company will specify that particular material and the supplier as the sole source for the initial supply contract, provided the new product meets all of the specifications.

Development agreements have become more common in recent years. Obtaining an agreement of this kind effectively leads to single sourcing⁷. It is a strategy which provides some incentive to the materials supplier to meet the necessary developmental targets, while allowing enough flexibility to both the supplier and the customer. Single sourcing can be advantageous to the automotive company as well, because it promotes a good relationship with the supplier, fostering higher product quality.

⁷ Single-sourcing is the practice of purchasing a material and/or a component for a specific application from a single supplier. For example, Xenoy[®] material for Ford's bumper systems is single sourced.

7.2 JOINT VENTURES

In a joint venture, two or more companies combine expertise in different areas in order to penetrate a new market area. Joint ventures divide innovation expense and utilize already existing product distribution channels, and capitalize upon well-established reputations.

Azdel Inc., the joint venture between General Electric and PPG mentioned in Chapter 6, was formed recently in order to market a new thermoplastic laminate material made from the advanced engineering resins that G.E. produces and PPG's glass fibers. The fact that the two partners are not direct competitors is significant.

Although as yet no other joint ventures have yielded plastic automotive materials innovations at the present time, materials suppliers may form joint ventures with custom molders, who have experience manufacturing parts for the auto industry. This could be an especially interesting strategy for new entrants in the automotive market, i.e., polymer producers who have not traditionally supplied the automotive industry and who could take advantage of the reputation of an already established custom molder.

7.3 UTILIZATION OF EXISTING RESOURCES

It was initially postulated that the possibility of utilizing existing resources (i.e., prior knowledge, expertise, manufacturing facilities, or existing equipment) might be a cause for innovation. It was assumed that

the materials suppliers who were already producing constituent resins could blend them together to produce an innovative product. This could take advantage of their production capacity, and of their expertise with the constituent materials. It was found that the availability of existing resources does not cause innovation, but is merely a desirable condition for successful product development. Rather than find a new application for a product they are already manufacturing and/or selling, materials suppliers need to penetrate a market that offers a large sales potential.

An examination of the cases of G.E.'s Xenoy® product, and DuPont's Bexloy® products supports this strategy. A polycarbonate product marketed under the name "Lexan®" was developed by G.E. Europe for European bumper systems prior to the development of an all-thermoplastic bumper for U.S.-made vehicles. It was not adequate for U.S. bumper systems, however, because it didn't meet the Federal Motor Vehicle Safety Standards. Therefore, Xenoy® (a PC/PBT product) was developed not so much to utilize materials and expertise that G.E. had acquired when developing Lexan, but to develop a material that could meet the necessary engineering and economic requirements. Although the experience G.E. had developing materials for European bumper systems could be an advantage, this was not the driving force for innovation.

DuPont developed an innovative amorphous nylon product for the rear quarter panel of the Fiero with similar motivations. A new product, Bexloy C®, had to be invented in order to penetrate the automotive exterior market,

because the traditional crystalline material was not adequate for body panel applications.

The cases of Bexloy C[®] and Xenoy[®] indicate that existence of resources does not necessarily cause innovation to utilize those resources, and that it is not a prerequisite for success. Hercules had attempted to manufacture composite automotive driveshafts to utilize its expertise and filament winding equipment. However, the product failed and the company was not successful, proving once again that existing resources do not necessarily cause successful innovation.

7.4 SUMMARY

A close working relationship between supplier and automotive company is fostered by the existence of contractual agreements for developmental work. It is an important strategic choice for the materials supplier to strive for a developmental contract, because it can lead to single sourcing, i.e., it can give the materials supplier a larger market potential than would otherwise be possible with many sources. Development contracts are also a wise strategic decision for the automotive company because they encourage a higher level of quality and reliability from a smaller number of highly motivated suppliers.

Because U.S. automotive companies have dictated the direction of materials/process innovations, materials suppliers should follow a strategy of mutual working relationship with the automotive company. One way to do

this is through development programs. Another strategy to penetrate the automotive market is the formation of a joint-venture with another company which has well-established communication channels, as is the case with the TP laminate material now marketed by Azdel, Inc. Utilization of existing resources, on the other hand, does not significantly affect the potential success of innovative suppliers.

8. CONCLUSIONS

The purpose of this work was to explain the role of innovation in materials substitution in structurally demanding applications in automobiles. A historical perspective is essential to better predict future developments, and to help supplier strategies. The research explained the role of innovative functional groups (suppliers and users of materials) that operate within the automotive industry. By using a consistent framework, the factors that led to the adoption of plastics and composites in structurally demanding applications in automobiles were identified.

Components made of plastic or composite materials were studied in detail, and the data gathered were used as a basis to identify the driving forces for the use of new materials. Three types of driving forces were identified: economic factors directly related to the materials studied, i.e., prices of the polymeric raw materials and the cost of labor to produce the parts; technological innovations in polymeric materials and/or the forming processes; and, the demand for new materials by the automotive industry.

An important finding was that the U.S. automotive companies caused technological innovations as a result of exogenous market forces which decreased sales of American-made vehicles in the 1970's. The automotive companies were in a position to drive technological innovations because of the large market potential offered to the suppliers by developing a product for structural or semi-structural applications. The market potential for a structural or semi-structural component can bring sales to the materials

supplier generally between 5 million dollars and 50 million dollars per year.

Innovative applications of engineering plastics and composites for automotive use were not held back by a lack of technology. Rather, the innovations did not take place earlier because there was no necessity for them. When the need arose, the technology was developed and implemented.

It was found that materials suppliers often bore the innovation burden, in the expectation of penetrating a potentially large market. Increasing sales was the only incentive for materials suppliers to innovate; innovation was the materials suppliers' response to a perceived increase in demand. Other reasons for supplier innovation that were initially postulated were found not to be the driving forces for innovation.

This work has shown that in order to be used or substituted, the innovative part must:

1. meet performance requirements as suggested by the user (i.e., the automotive company);
2. be cost-competitive with the part(s) being replaced; and
3. show potential for increased sales to the materials supplier.

This research has pointed out those strategic elements that can affect supplier success. It was determined that a long supply contract was unnecessary for supplier innovation and, furthermore, that it could have negative effects on both the supplier and the customer. Obtaining a development contract from the automotive company, on the other hand, was desirable to the material supplier (although not necessary for supplier innovation). Development contracts could foster single sourcing, however, and thus provide a greater incentive for supplier involvement. It was found that for a supplier to be successful, it need not innovate to utilize existing resources. Existing resources may be useful, but they do not cause the innovation.

As part of this study, it was necessary to make estimates of the market size for advanced plastics and composites. When making the estimates it was found that substitution of new materials took place part-by-part, and generally one vehicle model at a time. This is a non-optimal way to make materials substitution, because the new materials (i.e., the polymer) and processes must be developed in such a way as to behave like traditional materials (i.e., steel). However, through the interviews, it was determined that in the near future (up to approximately 1992), substitution by plastics and composites will continue part-for-part in a few selected car models.

The primary candidate applications for future substitution of plastics in autos will continue to be body panels. Development contracts will be awarded to single suppliers for selected car models, to develop not only

materials, but also tooling. Structural components that are likely to be developed from composites are floor pans and load floors, door structures, and entire front quarters, using reinforced thermoplastic sheet, structural RIM (reaction injection molding), and RTM (resin transfer molding).

To conclude, U.S. automotive companies will effect innovation in materials and processes because of the large potential market offered to the successful supplier. The materials supplier will be successful if it can comprehend the requirements of the automotive company, and obtain a development agreement.

APPENDIX A. - CASE STUDIES

This Appendix includes the data gathered for each component studied. The historical developments, applications and technology are presented for each case.

AZDEL COMPONENTS

Azdel® is the tradename for the material produced by Azdel, Inc. (a G.E.-PPG joint venture), which is a thermoplastic sheet reinforced with continuous glass fibers. Glass reinforced thermoplastic sheet was introduced around 1974, and the idea originated from Union Carbide in the late 1960's.

The first automotive application was in 1974, in the front end retainers i.e. where the lights are. The material was not developed specifically for automotive applications. However, the automotive industry offered the largest potential market.

The structural applications in U.S. automobiles are: the Corvette bumper beam, starting with 1985 models; the Cadillac Eldorado and Seville front and rear bumper beams; and the load floor in a variety of station wagons. These applications are all based on a polypropylene matrix reinforced with 40% continuous glass.

The process for molding Azdel is rather straightforward. It is a melt flow forming process in which glass-fiber reinforced plastic in sheet form flows into a mold and fills out the cavity of the tool as it is closed rapidly under high pressure. The molding process is composed of three basic steps: 1) heating the material, 2) compression molding the part and 3) solidification and part removal. Four basic pieces of equipment are required for the molding operation: an oven, a mold, a press, and a mold temperature control unit.

The stampable thermoplastic composite sheets are pre-cut and heated for 120-180 seconds, typically in an infrared oven above the melt temperature of the resin (425°F) before being placed in the mold. The blanks will be hot and pliable, but will not pull apart.

The resin has a high degree of mobility within the mold, and coverage may be as low as 50% of the part area. This implies design freedom for variations in wall thickness.

Rather than using a single sheet of material, parts are formed by stacking on the mold multiple pieces that have been cut to a size smaller than the outside dimensions of the part. These premeasured blanks are sized to be equal to the part volume and weight, thus there is 100% material usage in the molding operation.

The blank is then placed in a matched metal mold within a vertical press. The molding pressure required is on the order of 1500-2000 psi. Normally a

hydraulic press is used. The resin inside the mold is cooling rapidly and increasing in viscosity.

Tooling - compression molds with vertical telescoping sealing edges are appropriate. The material acts as a brake. There are no stops other than those for protection against full contact close. The dies are volumetrically variable. They depend on the material charge for their part volume. A single cavity tool can typically produce 290,000 parts/year.

Large Azdel parts are bonded together by electromagnetic welding - a method that uses inductive heating of a thermoplastic tape or ribbon containing conductive material, which is placed at the joint interface. The heat developed in the conductive film melts the thermoplastic part by convection.

The automotive components made of Azdel are electromagnetically welded. They are the largest and most complex components that use this technology.

In the Corvette bumper, Azdel is used in the load transfer beam. In the Cadillacs, the Azdel bumper beam has shock absorbers to meet the impact safety standard.

The Corvette bumper beam is a unique product. It is made with Azdel PP in 2 U-channels, electromagnetically bonded. The custom molder, LOF Plastics, delivers the beam as a bonded structure weighing approximately 12 lbs, and approximately 5 ft. long. It is sold for 30 \$/unit [7, 39, 52].

THERMOPLASTIC REAR QUARTER PANEL - BEXLOY C

Bexloy is the name of a venture formed by E.I. DuPont de Nemours, within DuPont, to develop materials for the automotive exterior. Different letters denote different materials:

C - amorphous nylon - used in Fiero rear quarter panel.

J - thermoplastic polyester

V - thermoplastic polyester elastomer - potential for rocker panels on 1991-1992 models.

M - polyarylate (part of the Arylon announcement) - for doors and fenders of future Fieros.

W - ionomer

Bexloy C is currently was used in the rear quarter panel of the Fiero.

The Bexloy venture was started approximately three years ago, in an effort to bring together research, manufacturing and marketing, for the purpose of developing materials targeted to a very specific market sector. This is a somewhat new philosophy at DuPont: traditionally, DuPont invented materials and then found applications and markets for them.

With the Bexloy venture, DuPont has developed materials which it did not traditionally supply. Bexloy C is an amorphous nylon material, whereas DuPont has traditionally supplied crystalline materials: Zytel, a crystalline nylon, has been in production for years.

The rear quarter panel of the Fiero is molded by GM's Oldsmobile Division, and DuPont thus supplies GM directly. The panel is injection molded using conventional technology, and there were no innovations in the processing technology. The material, on the other hand was developed specifically for the rear quarter application. The design for the panel was done as a co-operative effort between DuPont and Pontiac.

POLYURETHANES AND RIM

A material which found application in body panels of the Fiero vehicle was developed by Dow Chemical Co. It is a RIM-polyurethane material with internal mold release.

The addition-polymerization of polyols with polyisocyanates yields polyurethanes. The basic building blocks are isocyanates containing two or more isocyanate groups, and polyols containing two or more hydroxyl functions.

In RIM, highly reactive liquid systems are injected with high pressure impingement mixing into the mold. The part is then demolded [66].

Dow became involved with developing RIM products in the 1970's. Back then, the RIM materials that were available on the market had cycle times between 3 and 7 minutes. They also were problematic because they had turbulent viscosity which caused air entrapment, consequently exhibiting poor surface quality and high reject rates.

In 1979, Mobay introduced amine chain extenders, which decreased the cycle time (to 2 minutes) and improved the surface quality of the part.

However, the cycle time was considered still too high by the automotive companies. The longer cycle time effectively increases the cost of each molded part, by requiring higher capital and labor investments.

Dow's approach to reduce piece cost was to develop an internal mold release (IMR) product which was introduced in 1983, and scaled to full commercial production in 1984. This innovative approach increased molding productivity. With external mold release material it was necessary to spray the mold with release before each part was molded. However, with IMR material, 50 parts could be molded without cleaning the mold.

SMC HORIZONTAL BODY PANEL

SMC horizontal body panels with class A surface were developed in response to the announcement of the Fiero concept in 1979-80, which called for improvements in SMC.

SMC (sheet molding compound) is a thermosetting polyester sheet, reinforced with chopped glass fiber, and containing a variety of additives which act as fillers, catalyst, etc. The sheets are sticky and pliable, and are formed into a part by compression molding. The uncured SMC sheet is placed in a tool, and molded at temperature and pressure. The polymerization reaction takes place in the mold.

SMC material has been used in many applications within and outside of the automotive industry; for example, for truck panels [26] as well as for bathtubs and for appliance housings.

The use of SMC in the automotive industry evolved from the first application of FRP (fiber reinforced plastic technology) in the Corvette. In 1953, the Corvette's body was made of reinforced plastic by hand lay-up. It gave poor surface quality, non-uniform glass distribution and was a slow process.

Various improvements took place over the years: preforms were used which speeded up the process and made it more consistent from part to part. Low-profile formulations were also invented, where a thermoplastic additive improved surface quality [33].

In the early 70's, SMC was introduced, but there were still problems with porosity and pits in the surface. Although surface defects can be eliminated by sanding the surface of a molded panel, removing a part from the paint line to rework it is extremely inefficient and costly.

An innovative approach to address this problem was the development of in-mold coating. This consists of injecting a coating on the surface of the SMC part which is designed to eliminate the pits, and thus yield a class A surface without having to sand the part [14, 20].

This technology is used to mold horizontal panels of the Fiero and of the Corvette. Changes in the technology which made it possible to use it in automotive areas include a decrease in the scrap rate, as well as a slight increase in cycle time due to the added step of injecting an extra coat. The cycle times, which now are on the order of 90-120 seconds, are expected to decrease to 60 seconds by 1989.

The horizontal panels in production are molded by custom molders and not by the automotive company itself. Ashland supplies its Phase Alpha resin as a complete formulation for the horizontal panels.

LEAF SPRINGS

Innovation in Leaf Springs

The objective of developing composite leaf springs (both transverse and longitudinal) was to design and manufacture monoleaf composite springs with spring rates equivalent to multiple-leaf steel springs. This was to also result in a lighter weight component, with improved corrosion resistance and styling freedom for the vehicle body, as well as cost competitiveness with steel.

The Suspension System

The purpose of the suspension system is to eliminate or reduce the effect of variations in the roadway on the vertical acceleration of the chassis

i.e. to smooth the ride. This, in turn, also provides control of the vehicle. To do this, the spring component of the suspension system acts as an energy storage device. The energy storage is done in the form of elastic strain energy [11, 41].

Leaf Spring Design

Since in a leaf spring the energy is stored by flexure, the maximum efficiency is obtained if the stress in the spring can be uniformly distributed. With a constant cross-sectional area, this results in an outline for the spring that is linearly tapered in thickness and hyperbolic in width. Other loading conditions include forces that result from axle torque, longitudinal force and a twisting torque generated by the wheels. These forces tend to create shear stresses in the composite [11].

The transverse leaf spring, such as the one used in the Corvette, functions solely as a springing member, and does not react to cornering or braking loads. The design is a constant stress monoleaf spring of varying width and thickness. The spring is progressively wide and thin towards the ends, and the load is carried by a thick and narrow center section [16]. Longitudinal springs, such as those used in vans, are required to carry acceleration, braking and cornering loads, as well as suspension loads [36].

Materials

Both transverse and longitudinal leaf springs currently in use are made of epoxy reinforced with glass fibers. Hybrid concepts have also existed [9]. Glass-reinforced polyesters and vinyl esters were also candidates for the component as they would have provided faster curing rates. They were not used, however, because they exhibited inadequate creep and fatigue behavior [41].

Processing

There appear to be two processes which are suited for production of leaf springs: pulforming, and filament winding followed by compression molding. Pulforming was developed by Goldsworthy and it borrows from pultrusion technology: it consists of pulling glass rovings through a resin bath into a die. However, instead of a stationary mold, several molds are in motion on a horizontal rotor.

Filament winding followed by compression molding is the other process, rumored to be used by both Ford and the Inland Division of General Motors. Filament winding insures proper fiber impregnation and positioning; compression molding is used to eliminate voids and to speed up the curing reaction.

Filament winding itself is a rather old process and a variety of components, ranging from cherry pickers to rocket motor cases have been wound for decades. The adaptation of the process to high production rates and demanding engineering requirements is very innovative however.

Although fine details of the manufacturing process are not available, because of the high degree of proprietariness, some elements of the process can be inferred.

A conventional filament winder (such as the W-60 machine supplied by McClean-Anderson) is the building block for the process. The machine has then been adapted to a very sophisticated level by the user (the automotive company). The fiber rovings, after going through a resin bath, are wound onto a "mandrel" which is actually a drum with multiple cavities into which the impregnated rovings are placed. The drum is estimated to be 6-7 ft. in diameter.

A fabrication technique for an experimental leaf spring is discussed in [34], where a similar setup is reported. The tool used in the experimental process was a triangular wheel with a wooden core and polyethylene mandrel. Three springs could be made per wheel.

GKN, in the United Kingdom, also uses a proprietary process probably similar to the ones described above. The initial concept was of Bridon Composites in England approximately 10 years ago. Bridon was then bought out, and GKN bought the license on the technology. It is thought that GKN molds a 7-ft. wide piece and then slices to make the individual springs.

According to some of the people interviewed, filament winding is preferred because the cross-section of the spring can be changed (whereas with pulforming the cross-section is constant) and the fibers can be placed to

optimize the design. Basically, filament winding is a well-known, controllable process, the pulformer is difficult to use.

Historical Developments

The thought of composite leaf springs was pioneered by the Inland Division of GM in 1963, with some prototype work, through 1967, but the project was then abandoned. The prototypes did not give adequate performance results. In the mid-1970's, energy considerations became important, and in 1977 the project was started up again.

The 1981 Corvette had a fiberglass mono leaf spring in the rear suspension, and in 1982, both front and rear suspensions had a composite monoleaf spring. In 1986, the Cadillacs, Toronado, El Dorado, etc. have transverse fiberglass leaf springs.

Some sources say that the development of longitudinal springs for light trucks was initiated by Ford, who then solicited both fiber and resin suppliers for their materials. The design work was done in-house however, because Ford felt that they had more expertise in CAD/CAM, FEMA and optimization.

Ford light trucks have two longitudinal springs. They must be competitive with steel, which is 37\$/vehicle (i.e. 37\$/pair of springs). The initial run was 600,000 units per year, and the springs weigh 40 lbs/vehicle.

In 1985, GM mid-size vans (such as the Astro-Van) started having 2 composite springs per vehicle, in longitudinal position [16]. In 1985, GKN also started to produce longitudinal springs for the Freight Rover, a British Leyland light truck. Ford however, thought that GKN's springs were too expensive. Renault and Fiat also have composite longitudinal springs on small commercial vehicles of up to 3500 kg. These generally are produced in 20-30,000 units per year.

The leaf spring concept is disappearing from European vehicles because they do not give enough comfort. The Fiat Regata and Fiat Ritmo have back transverse steel springs which are also disappearing in future models.

A STEEL VERSUS A COMPOSITE LEAF SPRING

PARAMETER	CORVETTE COMPOSITE TRANSVERSE SPRING	CORVETTE STEEL SPRING
weight	3.6	18.6
number of leaves	1	10
modulus of elasticity (MPa)	37400	200000
elongation	5.00%	0.50%
design stress (MPa)	586	758
elastic strain energy (Nmm/kg)	2358	173
corrosive	no	yes
strength/mass ratio (relative)	5	1
fatigue life (relative)	5	1

XENYO BUMPER SYSTEM

The Xenyo bumper system is an all-plastic (excluding the shock absorbers) innovative system used by Ford for the Taurus, Sable and Aerostar, starting in 1985.

This system was developed entirely by General Electric to meet requirements of improved corrosion resistance, weight reduction, and cost competitiveness. Impact resistance of 5 mph was also a requirement.

The polycarbonate material that G.E. had developed for Ford Europe, for use on the European Ford Escorts [24], did not meet the standard of 5 mph

impact. Therefore, G.E. had to develop a new product. Xenoy is a PC/PBT alloy.

G.E. demonstrated feasibility of its all-thermoplastic system in 1978. Some material was sold in 1983. However, sales did not pick up until 1985.

Alloys are combinations of two or more resins mixed, usually in the molten state, to form a new material. Unlike co-polymers, grafts or IPN's, no chemical synthesis or formation of new covalent bonds occurs.

Alloys are characterised as either miscible or immiscible depending on the number of phases present. Miscible or soluble blends are one phase with one Tg. Individual polymer segments are intimately mixed with e.g. hydrogen bonding, donor-acceptor.

Completely immiscible alloys can delaminate during processing due to lack of adhesion at the polymer interface. A compatibilizer can be added to improve adhesion. market place, is driving current alloying and blending activities.

The effort diverges from the development of new molecules or new molecular weight grades, or the modification of properties by changing molecular weight distribution. The growing activity among materials suppliers is to take off-the-shelf resins and put them together in new ways to create a synergism yielding properties that were not available before. This concept has been implemented for some years, but on a much smaller scale. The dif-

ference is that the effort is much more sophisticated and intensified now that plastics have reached a much more positive degree of acceptance [47, 69].

The Xenoy bumper system used by Ford weighs between 21 and 23 lbs, averaging approximately 40 lbs of polymer alloy per vehicle. The bumpers were initially put on the Escort GT and Lynx RS between 1984 and 1985 as pilot programs. They were taken out at the end of 1985, and are expected to return on 1988.

The systems are produced at the Ford, Milan, MI. plant, in 2 shifts, 5 days per week. The bumpers are molded, linear welded and painted, and then delivered to the assembly plant. The system is therefore painted off-line. The paint is supplied by Redspot Paint and Varnish, and it is a primer-less 2 component polyurethane system.

COMPOSITE DRIVESHAFT

The filament winding process had to be modified to be able to produce large numbers of shafts (30,000/year). The innovation was to use a continuously winding mandrel which translates. This was developed by Hercules and also by Ciba-Geigy but separately. Ciba-Geigy is producing the shafts in Switzerland, and appears to be the only one left in this application.

The materials used now are glass fiber, carbon fiber, and an epoxy resin. Ford, which had solicited the driveshaft development, used the cheapest materials available on the market.

Drive-shafts were made, and for most cases still are made, as two steel tubes with a joint in the middle. The major problem with them is the vibration and hence the noise they make. It was not possible to make one long steel tube because it vibrated too much. By making the shafts out of composite, the vibration is reduced. They can be made in one piece, and thus can become cost competitive with steel by reducing assembly costs.

In the 1970's many companies were experimenting with composite drive-shafts: Hercules, Merlin Technologies (part of Celanese), Exxon Enterprises (they were overwrapping Aluminum with prepreg). Most people were wrapping fabric. All the ends were metallic: the shaft was fastened or bolted to the metal sleeve [9].

The first set of composite drive-shaft that worked was made by Merlin Technologies around 1977, and it was sent over to Ford U.K. It was reinforced with carbon and glass fibers. A contract was then given to Hercules by Ford for the Econoline, for a few thousand shafts. These were bonded and then bolted, but they apparently did not work very well. Hercules then got an order for another 10,000. Unfortunately, Hercules was apparently unable to deliver as contracted, and some sources indicate that the supplier, normally an aerospace contractor, was not fully aware of the constraints placed by the volumes of the automotive industry. The Astro Van however,

which had begun to use composite drive-shaft went to aluminum for cost reasons [29].

Composite driveshafts made by Ciba-Geigy were also put in the Aerostar. However, there were problems with the entire power train assembly, which had to be removed.

Drive-shafts are not used in front-wheel drive cars which are becoming more popular. They are used in minivans, such as the Econoline. Some people also say that they have some potential for 4-wheel drive cars.

Two elements will be described below: the driveshaft, and continuous filament winding (i.e. the Mark VI concept).

Driveshafts

In general, the rotational speeds of the drive train require the torque tube to have a high natural frequency [19]. The maximum speed-to-length ratio is limited because of resonance problems. Example: If the maximum speed of the vehicle is 90 mph, the shaft will rotate at 3600 rpm. The frequency is around 60 Hz. If you can't satisfy the natural frequency, you must use two pieces for the shaft.

The design of a driveshaft involves three elements: the shaft tube, the end fitting, and the end fitting attachment. The design criteria for torque tubes are as follows: static and dynamic torque load; axial load, which

implies critical speed, length, diameter, environment. For equations and more details, see reference [2].

Continuous filament winding - the Mark VI concept

In a typical filament winding machine, a single layer of fibers requires multiple passes for full coverage, such that a typical winding rate is one shaft per hour. The Mark VI concept was designed to obtain winding rates of one shaft per minute. The reinforcement, impregnation and delivery systems remain stationary, while the mandrel is both rotated and longitudinally translated past the delivery system. The machine is also equipped with automatic devices for transferring from one reinforcement type to a second. For diagrams, see reference [19].

APPENDIX B. - OVERVIEW OF THE U.S. AUTOMOTIVE INDUSTRY

This Appendix is intended to give a brief overview and examples of firms involved in the U.S. automotive industry in terms of materials and manufacturing (not of labor relations or other political issues). Examples of manufacturers will be given, but this Appendix is not intended to be an exhaustive guide to the automotive industry. Extensive lists of manufacturers and suppliers can be found elsewhere [53, 66].

There are the "Big Three" automotive manufacturers, who are the focus of this thesis. They are: General Motors Corporation, Ford, and Chrysler, and they are all headquartered in the Detroit area. Vehicle assembly facilities are located throughout the U.S.A. Assembly lines in the U.S. run an average of 60 cars/hour, i.e., one car is assembled every minute. Hence, cycle times of one minute per part are often considered the ideal time frame.

Materials substitution, and technological innovation in general, are often constrained by existing equipment and manufacturing practices. For this reason, technological innovations often have to evolve in such a way as to make a new component essentially similar to the traditional one. For example, one of the biggest challenges that polymeric materials face for body panel use, is that they need to withstand temperatures of 350 degrees F or more, if they are to be painted on-line with metal parts.

Each of the automotive companies buys parts and components from their own divisions or from OEM's (original equipment manufacturers). A large number of plastic and composite parts are purchased from custom molders.

Examples of custom molders include:

Budd (SMC)

Diversitech General (SMC)

Rockwell International (SMC)

Premix (SMC)

Magna (RIM)

LOF Plastics (thermoplastic stamping)

Divisions of the automotive companies which supply plastic components include:

Paint and Vinyl Division (Ford, injection molding)

Oldsmobile Division (GMC, RIM)

Inland Division (GMC, leaf springs)

There are then a variety of manufacturers of equipment for fabricating the plastic components. Examples are:

McClellan-Anderson (filament winding)

Kraus-Maffei (injection molding)

Williams-White (presses)

Erie Press Systems (SMC presses)

Polymeric materials are supplied to the automotive companies for structural applications, body panels, decorative parts, car interior and under-the-hood components. Examples of said suppliers are:

General Electric, Plastics Div.

E.I. DuPont de Nemours

Borg-Warner

Mobay

Ashland Chemicals

The Dow Chemical Co.

Owens-Corning Fiberglass

PPG Industries

The materials suppliers have sales offices in the Detroit area to facilitate contact with the "Big Three". Some of the suppliers also have Automotive Tech Centers, which provide technical support to the automotive companies. For example, they do some prototype work, or develop tooling to promote their materials.

APPENDIX C. - COST MODELING METHODOLOGY

Process cost models have been used extensively throughout this research. Exhaustive discussions on the cost modeling methodology developed by the Materials Systems Laboratory at M.I.T. can be found elsewhere [5, 6, 28, 29, 35, 37, 71], and therefore only a brief description of the overall methodology will be given here.

This Appendix discusses a systematic method for estimating costs of processing and fabrication applicable to the materials industry, using the format of an interactive spreadsheet.

The cost modeling described here is based on work developed at the Materials Systems Laboratory using an IBM Personal Computer, and Lotus 123® software. This consists of a very large worksheet, similar to a financial ledger sheet, ruled into rows and columns. Each "cell" in the worksheet, which corresponds to a unique row and column "address", can store a piece of information: a number, letters, words, or a mathematical formula to calculate a value [72]. The following discussion will follow the actual format of such a spreadsheet, but cost models are not restricted to this specific layout.

The objective of cost modeling is to develop consistent estimates of the costs associated with processing a material into primary, semi-finished or finished products. In doing such work, the analyst attempts to model the technology for the process as closely as possible, and to calculate the

value of all the inputs associated with this process. These include the raw materials, energy, labor, equipment and capital, each of which is process-dependent.

Cost estimates have traditionally been used to "predict the expenses that must be incurred to manufacture a product" [43], which can then affect the product manufacturing decision. They are also valuable tools for evaluating and comparing manufacturing alternatives, and for determining the most economical method of manufacturing a product.

Cost estimates are used for many purposes: they can serve as a guideline for the type of tooling, personnel and materials requirements necessary for successful manufacture of a product, and also provide a reference for production efficiency. In addition, they can be used to evaluate the costs and potential success of a competing product, and to evaluate design proposals. Estimates are also necessary in making investment and bidding decisions [43], and to measure profitability. In this thesis, cost models have been used to compare the cost of making an equivalent component of engineering plastics versus steel. Additionally, the models were used to examine how technological change affected process economics.

Cost models built using the electronic spreadsheet approach allow for cost estimates based on alternative sets of assumptions. The cost model can then be used to assess the potential feasibility of various materials and processes for given applications. The user-interactive, computerized nature of the cost model is particularly suited for examining different

processing alternatives, and for estimating how possible changes in the processing technology affect costs.

The methodology presented in this Appendix is also useful for analyzing the effects of technological change and innovation on piece cost. It is particularly useful for identifying the contribution of each element to the total cost, and where effective changes can be made to the process in order to decrease the costs. This is effectively how the cost models have been applied in this research. The models also provide important information for inclusion in analyses of demand and consumption of a given product, based on trends in processing technology and market assumptions.

The first step in building a cost model is to divide the process of interest into unit operations by creating a flow-diagram. The diagram fundamentally illustrates the steps necessary to produce a given material or component, and may include inputs to each operation. The flow sheet enables the clear conceptualization of the process, with an understanding of how each step relates to the others, and which operations may be optional.

The spreadsheet is divided into sections which include:

1. factor prices (such as price of raw materials),
2. input factors (such as cycle times),
3. and a framework for each of the steps specified in the flow diagram.

The segmentation is used to clearly define which variables are exogenously input, and which are endogenous to the model.

Factor prices and input factors refer to all those variables which are entered exogenously in the model, and which determine the final cost. The nature of the spreadsheet makes it easy to itemize the parameters, which can then be individually changed to study their effect on the final cost. It is usually advisable therefore to disaggregate the variables as much as possible, particularly when a detailed analysis is desired.

Determining the cost of a process step requires calculation of capital-related charges, materials, energy and labor costs. These are calculated on a per unit basis for each process step, where per unit refers to dollars per pound (\$/lb) or dollars per part (\$/part), and are totalled at the end of each unit operation.

Price information obtained from manufacturers is usually reliable especially when the actual selling prices are quoted. Reputable textbooks and journals are also good sources, but it is always advisable to verify published information with the manufacturers directly, particularly for updated prices and new processing developments.

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BIOGRAPHICAL NOTE

I was born on March 4, 1963, in Milano, Italy. I attended the International School of Milan for 11 years. Then I attended two years of High School at Queenswood in England. I came to M.I.T. as a freshman in September 1980. I obtained a Bachelor's degree in Materials Science and Engineering in February 1984, and a Master's degree in August 1985.

I have spent time traveling to various countries both for pleasure and for educational purposes. After obtaining the Ph.D. degree on June 1st, 1987, I will move to Milano, Italy, with my husband, where we hope to have exciting careers.