Future of Polymers in Automotive Applications

by

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B.Sc. Materials Engineering
Queen's University, 1993

SUBMITTED TO THE DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREES OF

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Abstract

A dynamic projection methodology was developed to anticipate likely future plastic composite consumption in the automotive market and the impact of various scenarios. This methodology, which is meant to be used to inform strategic supply and demand decisions, was built on a part-by-part substitution analysis and utilizes logistics curves and technical cost models. Current plastic and plastic composite automotive content was segmented. Emerging plastic composite automotive parts and systems were classified according to their cost and performance attributes. Technical cost models were used to establish cost attributes of newly designed composite systems. The substitution of these parts and systems was based on four representative historical plastic substitution examples.

In the baseline projection, plastic composite content in an average North American vehicle was projected to increase from the current 223 pounds to 324 pounds in 2015. Global automotive plastic composite consumption was projected to increase from 9.3 billion pounds to 18.3 billion pounds by 2015. The scenarios considered were: the increasing of fuel economy legislation, the tightening of recycling legislation, the development of a revolutionary composite intensive vehicle, and the development of incremental design, manufacturing, and processing advances. Baseline and scenario projections of future plastic composite content in an average vehicle were generated for North America, Western Europe, and Asia. Probabilities were assigned to potential outcomes. The expected value of global automotive composite penetration in 2015 was projected to be between 16.6 billion pounds and 20.5 billion pounds.

Thesis Supervisor: Dr. Joel P. Clark
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List of Figures

List of Tables

Acknowledgments

Consolidating and writing up the results of two years of independent work has been a very challenging process. The support, encouragement, and bantering of my colleagues and friends in the Materials Systems Laboratory have made the process immeasurably more rewarding. I'd like to take this chance to remind Randy Kirchain, J. Neely, Sam Newell, Dr. Richard Roth, Luis German, Paul Kang, Deirdre Pettigrew, Maija Lokka, Harsha Marti, Anil Jain, and Brian Zuckerman that "the world needs more Canada." Thank you for all the intriguing discussions, for the timely thesis help, and for the advice, support, and laughter.

I am grateful to Dr. Frank Field, director of MSL, for always making time to answer my many questions and for increasing my vocabulary extensively! I have also been very fortunate in finding a supervisor as supportive as Dr. Joel Clark. Thank you, Joel, for your mentorship on my research, interest in my future career direction, and concern for the well being of myself and all the members of our research group.

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My heartfelt thanks to Toffer Winslow, for sharing in the joys and sorrows of the past two years. And lastly, I'd like to thank my family for their love, constant encouragement, and high expectations.

Chapter 1: Background

1.1 AUTOMOTIVE MATERIAL SELECTION

The selection of automotive materials is a key component of automobile product competitiveness. Material choice and product design are tightly linked. The choice of a material limits the kinds of material forming processes which can be used, which in turn limit the degree and type of part complexity that can be achieved. Although cost reduction is always an objective, new materials or new design applications of existing materials have significant barrier to overcome before acceptance into automotive applications. Liability concerns, designer unfamiliarity, and existing infrastructure can all slow down the acceptance of a new material.

Steel is the dominant material used in automotive production, comprising over 60% of a typical vehicle's weight. Aluminum and plastic composite suppliers are vitally interested in conveying to automotive designers the strategic advantages of their material and process advances. Structural polymer composites systems are the least well understood by the automotive designer community. Sheet Molding Compound (SMC), Resin Transfer Molding (RTM), Structural Reaction Injection Molding (S-RIM), and Glass Matte Thermoplastics (GMT) have been undergoing design and process advances that could initiate major changes in material usage in structural automotive applications. This thesis is focused on the potential impact to plastic composite consumption in automotive applications under forces both internal and external to plastic composite technology.

1.2 HISTORICAL PLASTIC COMPOSITE SUBSTITUTION INTO AUTOMOTIVE APPLICATIONS

Polymers have been used in automotive interiors since the 1930s for such applications as molded gear shift knobs, steering wheels, and water pump gears. With the development of Fiberglas and polyester body panels in 1953, polymer composites became an alternate material choice in exterior non-structural parts as well. Over the following two decades many advances were made to improve appearance while lowering rework. Today, for many platforms with production volumes of less than eighty thousand automobiles, plastic composite closures have brought both a cost advantage due to lower tooling costs (see figure 1.1) and an opportunity to achieve superior styling. Adoption has not been without major setbacks, however. Quality issues, including paint pops and thermal expansion mismatch, haunted the early automotive days of polymer composites. Quality can also vary significantly between suppliers to the detriment of the entire industry.

During the last two decades, plastic composite penetration into automotive applications has been gradual and appears to have been very uniform, as shown in Figure 1.2. However, the macro view of polymer growth disguises some very relevant trends in polymer substitution, including differences in penetration for different volume platforms and different dynamics behind interior, closures, and structural composite growth. An understanding of the driving forces behind the growth and decline of these subsectors is essential for any success in forecasting future evolutionary shifts in polymer usage in automotive applications. More dramatically, the hurdles to revolutionary changes in polymer penetration also need to be assessed. Carbon fiber price, cure time for RTM parts, and preform advances are all key parameters for a future economic, revolutionary plastic composite intensive vehicle.

Figure 1.1: Fender Production Costs vs. Volume

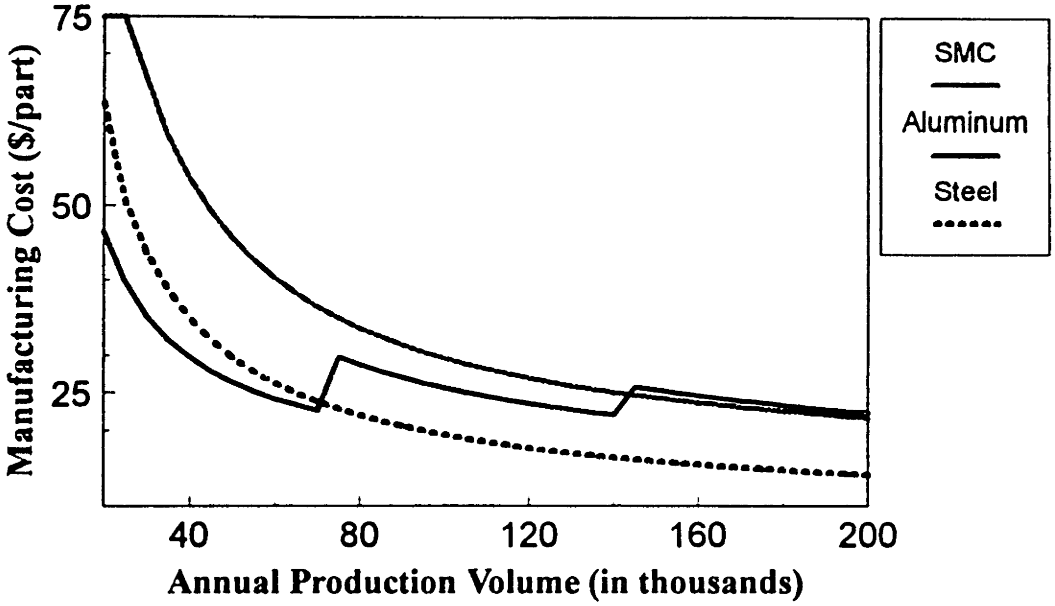
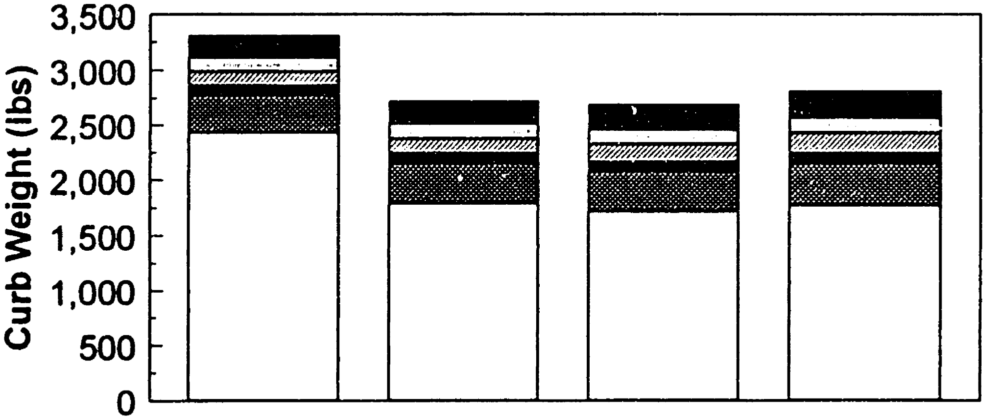


Figure 1.2: Material Composition of a Typical N.A. Family Vehicle



	1980	1985	1990	1995
Ferrous □	2,427.5	1,782.5	1,716.5	1,767.0
Other * ▩	344.5	366.5	359.5	381.0
Glass ■	87.0	85.0	86.5	91.5
Aluminum ▨	123.5	138.0	158.5	187.5
Rubber □	130.0	136.0	136.5	136.0
Plastic / Composite ■	196.5	211.5	229.0	246.5

At the same time that materials have become a part of product strategy, the automaker's material choice is increasingly influenced by factors external to traditional automotive concerns. Most recently, vehicle recyclability has emerged as an issue which is receiving world-wide attention, with thermosets receiving increasingly negative attention. Furthermore, stringent regulatory considerations, including the new Clean Air Act as well as the recent CAFE debates in the USA, are influencing the competitiveness of automobile materials. These external factors have the potential to have a strong impact on the growth or decline of polymer composites in automotive applications.

1.3 TECHNICAL COST MODELING TOOLS DEVELOPED BY THE MATERIALS SYSTEMS LABORATORY AT MIT

For the past fifteen years, the MIT Materials Systems Laboratory (MSL) has been studying materials selection and substitution within the automobile industry with a view toward the development of a synthesis of engineering, economics, and business planning knowledge. The MSL has been a leader not only in developing methods for treating such problems on an analytical basis, but also in employing these techniques to analyze the competitive position of alternative designs, materials, and processes.

Central to the work at the MSL has been the development of computer spreadsheet-based tools for analyzing the manufacturing cost implications of materials selection, manufacturing strategies, and business conditions. These tools have been used to evaluate not only the competitive implications of conventional materials and material forming technologies, but also developmental and research alternatives, quantifying the strengths and weaknesses of these alternatives as well as pinpointing the critical factors (both engineering and economic) which contribute to this competitive position. Technical-economic cost models[1] of plastic composite part fabrication processes, such as the resin transfer molding and sheet molding composite processes, as well as models of the steel stamping and assembly processes, provide a major analytical tool for this work.

1.4 LOGISTICS CURVE ANALYSIS

Fisher Pry's classic analysis on substitution[2] provides a simple model, logistics curves, for projecting materials substitution. Logistics curves (also referred to as S-curves) plot market penetration of a material in an application against the time it takes for the market penetration to occur. They are built using three assumptions: 1) Technological advances can be modeled as competitive substitutions 2) All viable substitutions that have proceeded past a few percent will proceed to 100% market penetration, and 3) The fractional rate of substitution of the new material for the old material is proportional to the remaining amount of old material in the application. In applications where assumption two is not accurate, logistics curves still provide a good model if they are applied only to the niche market in which they are viable throughout the substitution period.

A general logistics curve, depicted in Figure 1.3, is derived from the Fisher Pry equation, as follows:

$$f / (1-f) = \exp 2 G (t - t_0)$$

where, f is the percentage market penetration, G is one half of the constant percentage growth rate, t is the time since the innovation was commercially introduced, and t_0 is the time to 50% market penetration. Hence, knowing either the time until a specific market penetration and the constant percentage growth rate or knowing two time-penetration data points is sufficient to model the remainder of the substitution curve.

Tincher and Busch have used the Fisher Pry methodology to classify different plastic composite materials substitution curves according to their performance and cost characteristics.[3] Thus, if the relative performance and cost characteristics of a potential substitute are known, a projected substitution curve can be modeled on a known curve of the same type.

Figure 1.3: Fisher-Pry Logistics Curves

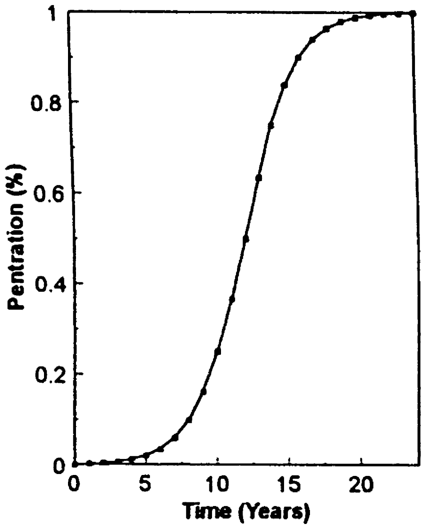
Assumptions

1) Technological advances can be modeled as competitive substitutions

2) Viable substitutions that proceed past a few percent will proceed to 100% penetration

3) The fractional rate of substitution is proportional to the remaining amount of 'old' material in the application

$$f / (1-f) = \exp\{2 G (t-t_o)\}$$



Chapter 2: Baseline Projection

2.1 OVERALL PENETRATION OF PLASTICS AND PLASTIC COMPOSITES INTO AUTOMOTIVE APPLICATIONS

The plastic composite content of an average car in North America, Europe, and Japan from 1995 until 2015 is estimated by means of a projected baseline and scenarios for deviation from that baseline. For North America, where extensive data was available on the individual car parts, the baseline is created by layering on performance / cost assessed future substitution of individual parts to the current penetration of exterior, interior, structural, and under-the-hood plastic composite parts in vehicles. For Europe and Asia, where less detailed information was available, the baseline is created by the vehicle growth rates and the plastic composite content growth rates shown in Appendix A.

Two main tools are utilized to quantify the impact of alternate scenarios on the baseline forecast. For cost-driven substitutions, technical-economic cost modeling is utilized to assess the manufacturing costs of emerging composite parts and systems relative to the incumbent material. Once the performance and cost attributes of a part are understood, substitution projections are modeled on the representative logistics curves applied to segments of the vehicle market where the part's performance and cost attributes are relatively constant. For the purpose of logistic curve modeling, the automotive market is segmented by total production volume (figure 2.1) and by class of vehicle (figure 2.2). For plastic composite parts, the economics of production are often based on low tooling costs, which enable composites to be competitive against steel parts at low production volumes. Vehicle class is also a relevant segmentation as customer requirements for performance are considerably different for an economy car than for a luxury car. Given acceptable performance standards, cost is assumed to be the dominant driver for economy vehicles.

For plastics and composites suppliers, the total estimated volume of plastic composites in the future is a more useful metric than pounds per vehicle for strategic planning purposes. Hence, total future consumption of plastics and plastic composites in cars and light trucks[4] globally is estimated through the multiplication of total future production of cars and light trucks in each region and the amount of plastic per average car in each region.

2.2 CURRENT POSITION OF PLASTICS IN AUTOMOTIVE APPLICATIONS

In North America, there are currently 223 lbs of plastics and plastic composites in the average vehicle.[5] For the purposes of this scenario analysis, total plastic content is divided into the categories of exterior, interior, under-the-hood, structural, and other mechanical, electrical, and flexible components, as shown in Figure 2.3. Figure 2.4 further details current applications in the largest category, interior applications. As interior applications make up 40% of automotive plastics consumption, it is not surprising that injection molding is the dominant process employed (figure 2.5). In North America, structural parts are currently mainly compression molded or filament wound. Although North American automotive producers employ the most pounds per vehicle of plastics, Western Europeans have the highest percentage plastics use due to lighter average vehicles as shown in figure 2.6.

Figure 2.1: Cost Segmentation of Automotive Market

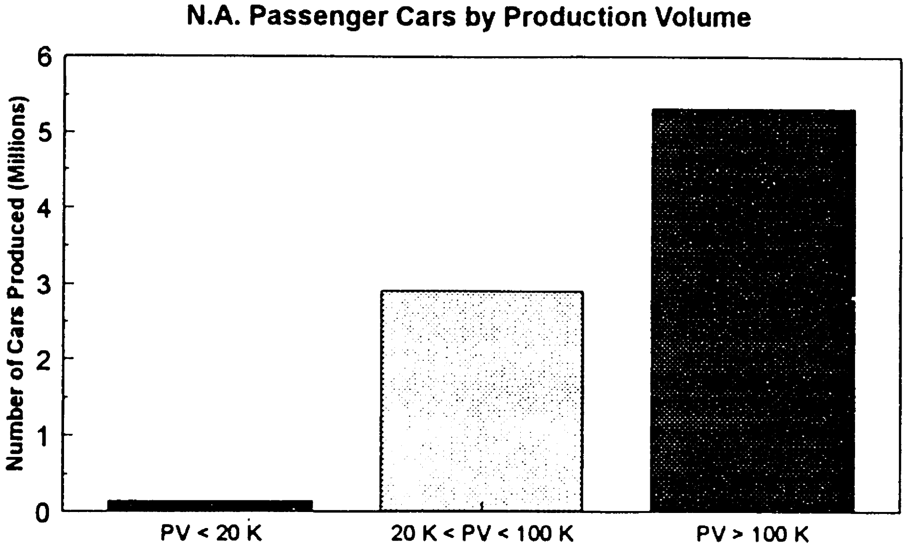


Figure 2.2: Performance Segmentation of Automotive Market

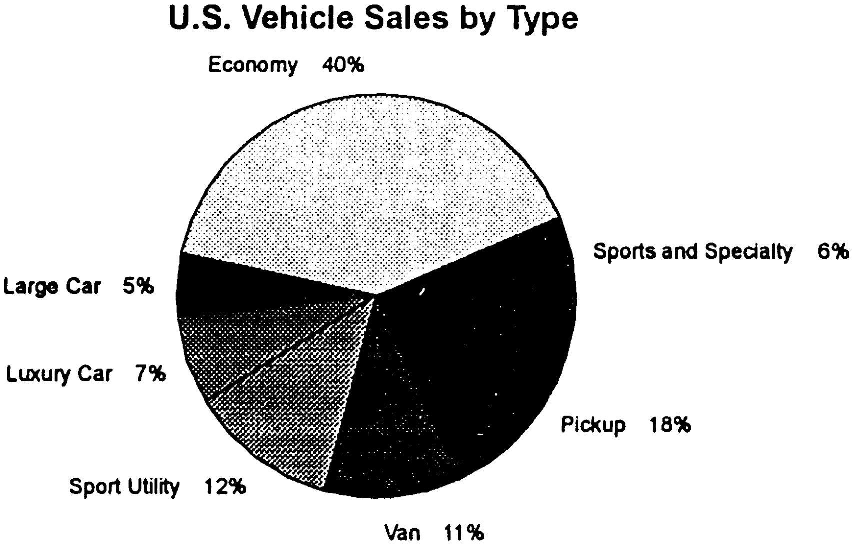


Figure 2.3: Plastics in 1995 Average North American Vehicle (lbs)

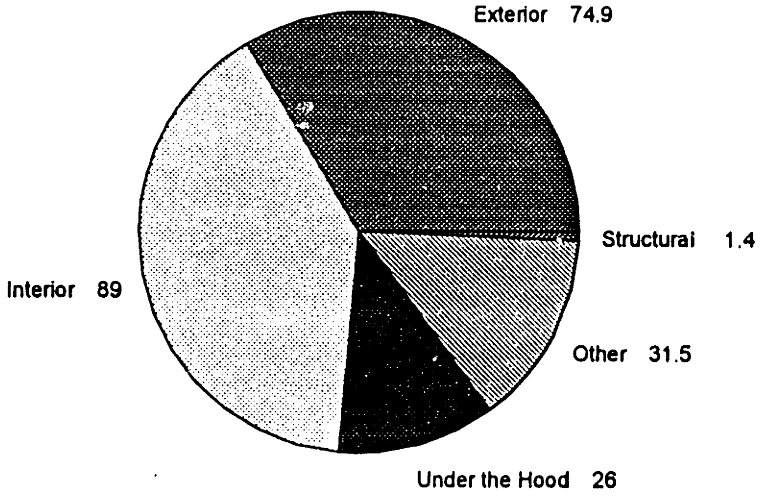


Figure 2.4: Interior Plastics in 1995 Average North American Vehicle

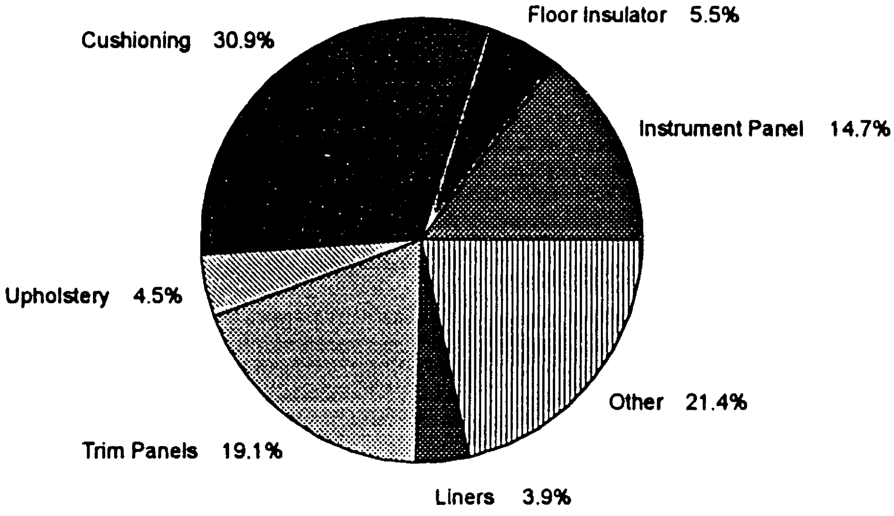


Figure 2.5: Plastic Processes used for 1995 North American Vehicle (MM lbs)

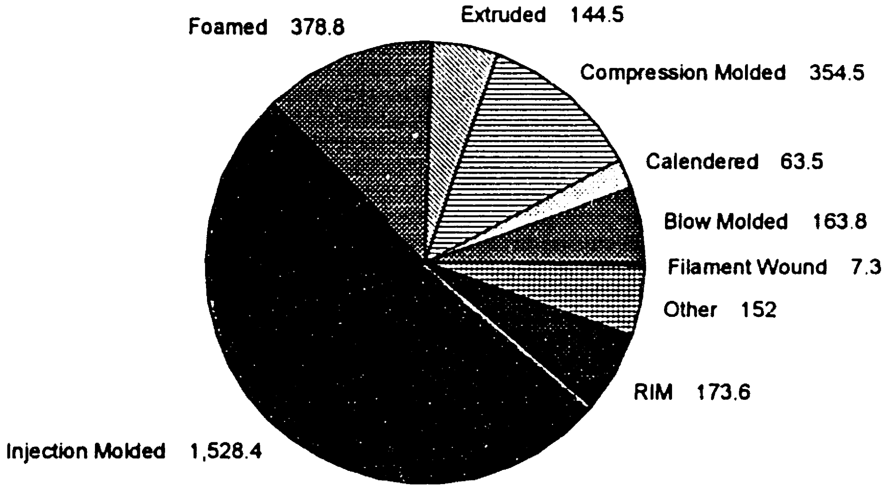
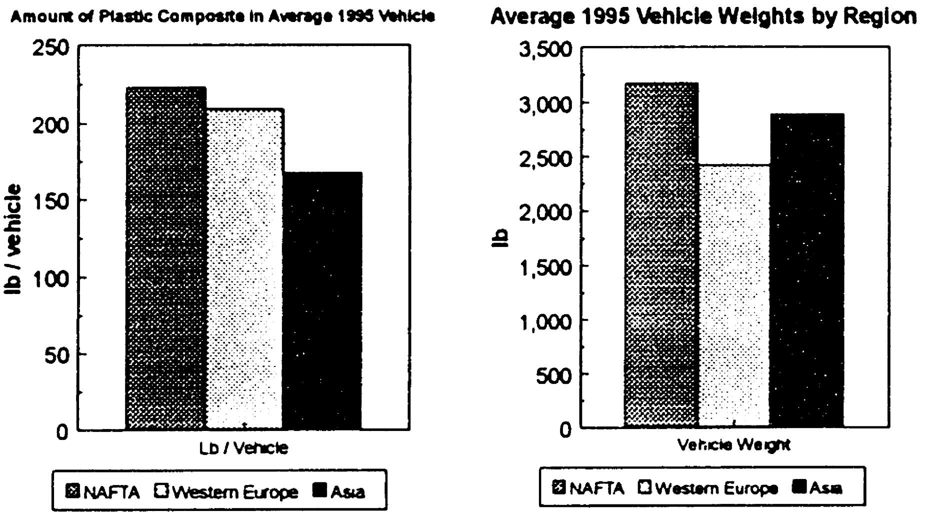


Figure 2.6 Regional Plastic Composite Content in Automobiles



2.3 BASE CASE PLASTIC COMPOSITE GROWTH / DECLINE IN APPLICATIONS

2.3.1 Driving Forces for Base Case Plastic Composite Substitution

The driving forces behind one-to-one substitutions of plastic for steel are cost reduction at low volumes, light-weighting, and resistance to dents and deterioration. Cost savings is the main force behind subsystem substitution (e.g. integrated front end system) due to parts consolidation and modular assembly advantages. Lightweighting and design demands are more modest drivers of plastic composite subsystem substitution.

2.3.2 Logistics Curve Penetration for Base Case Plastic Composite Substitution

Logistics curve[6] penetration on an individual part level is used for the base case projection and most of the scenarios. Projected penetration rates are based on known substitution curves for plastic composite parts that had similar cost and performance characteristics. The four types of cost and performance combinations for which materials substitution occurs are described below in Table 2.1.

	Cost	Performance	Examples	½ Growth Rate	Years to 50% adoption
Type 1	lower	higher	PVC window frames substituting for Al	27.5%	12
Type 2	lower	comparable	PVC drain pipes substitution for copper or iron	12.2%	17
Type 3	lower	lower	oriented strandboard for plywood	6.3%	26
Type 7	higher	higher	carbon fiber composite boat hull substitution for Fiberglas	11.0%	20

Table 2.1: Substitution Curves Used in Scenario Analysis

These plastic composite substitution examples, which are listed in Table 2.1 and shown in figure 2.7, are representative of the four types of substitution drivers. The curves in figure 2.7

have been extrapolated from the Fisher Pry equation in cases where the substitution is not yet completed. All substitution projections in this thesis are based on these four curves.

The four types of cost and performance combinations for which substitution will not occur are type 5 (comparable price, comparable performance), type 6 (comparable price, lower performance), type 8 (higher price, comparable performance), and type 9 (higher price, lower performance). It may seem unnecessary to classify cost and performance attributes when they are combinations that are uncompetitive. However, with advances in performance or technological cost-lowering advances, applications that currently are not competitive could be transformed to one of types 1, 2, 3, or 7.

In the baseline case, growth is projected based on vehicle growth estimates (see Appendix B), a ten year forecast of specific parts by Market Search[7], and long-term logistics curve modeling of specific parts. The parts on which logistics curve penetration forecasting is used in the baseline forecast are listed below along with the cost and performance type that each is modeled on. For different scenarios, the cost and performance type can change. For example, in the recycling scenario, ASR treatment cost is added onto the production cost of plastic composite parts, altering type 1 substitutions to the slower type 7 substitutions and type 3 substitutions to the uncompetitive type 9.

Part or Subsystem	**Logistics curve Substitution Type** Low Volume	**Logistics curve Substitution Type** High Volume	**Other Limitations** **(Niche Markets)**
nylon engine intake manifold	Type 1	Type 1	none
integrated front end system	Type 1	Type 1	cab forward
ABS / PP instrument panel	Type 1	Type 1	none

pickup box	Type 1	Type 7	pickup trucks
bumper beam	Type 1	Type 7	none
fascia	Type 1	Type 1	none
bumper energy absorber	Type 1	Type 1	none
SMC / thermoplastic front fenders	Type 1	Type 7	none
SMC / thermoplastic rear fenders	Type 3	Type 5	small volume and economy, sports, specialty, or van
SMC rear deck	Type 2	Type 8	small volume and economy, sports, specialty, or van
SMC hood	Type 1	Type 7	none
Side Doors	Type 3	Type 5	small volume and economy, sports, specialty, or van
Rear End Panel	Type 2	Type 8	small volume
Exterior Door Handles	Type 2	Type 2	none
Reinforced Nylon Wheel Covers	Type 2	Type 2	exclude luxury, specialty, and pickups
Trunk Liner	Type 2	Type 2	complex trunks
Alternative Vehicle, Structural	Type 7	not viable	50% of mandated ZEVs
Seat Shell	Type 1	Type 7	platforms under 20,000
Engine Oil Pan	Type 2	Type 2	none
Fuel Line	Type 1	Type 1	none
Fuel Pump	Type 1	Type 1	none
PE fuel tank	Type 1	Type 1	none

Table 2.2 Baseline Substitution Projections

2.3.3 Base Case Plastic Composite Substitution: 1995 to 2015

In the base case scenario, it is anticipated that plastic composite content in the average North American vehicle will grow to 324 pounds per vehicle by the year 2015. Figure 2.9 breaks out anticipated growth into types of application. 1% growth per year for North American vehicles is assumed. Figures 2.10 and 2.11, respectively, show the projections of absolute plastic composite content and percentage content for the regions of NAFTA, Western Europe, and Asia.

Figure 2.7: Basis for Logistics Curve Projections

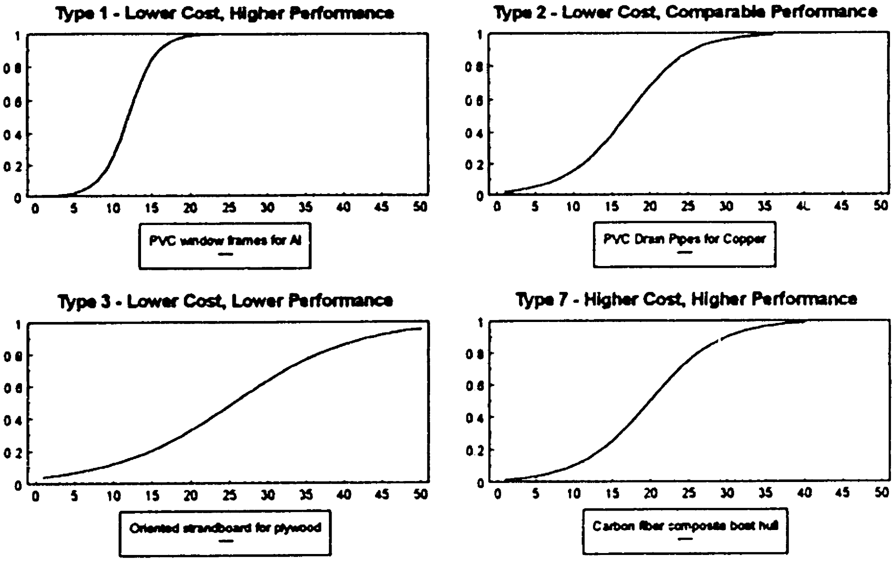
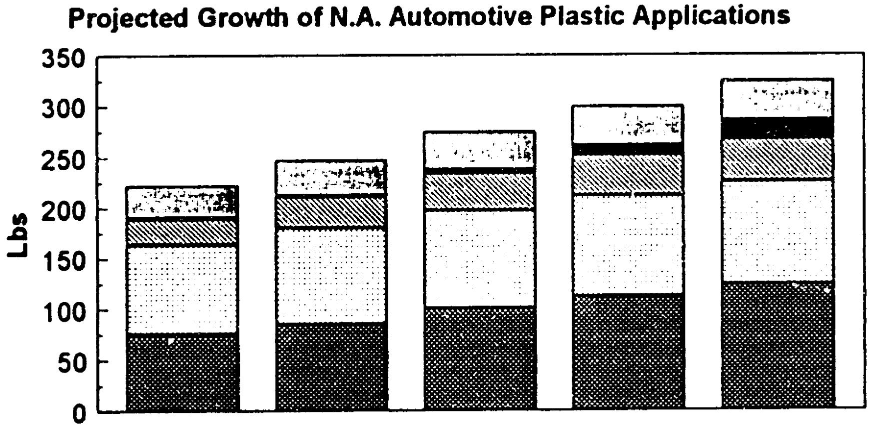
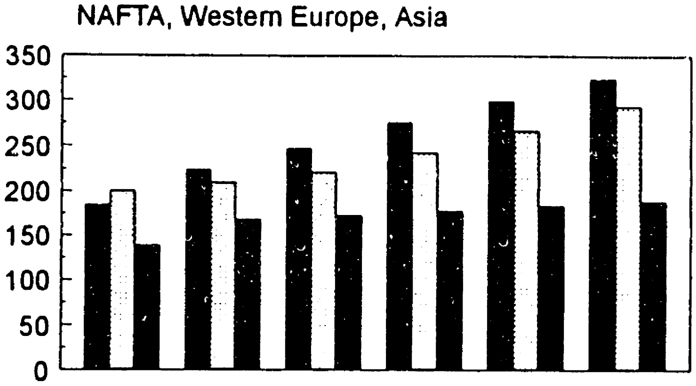


Figure 2.8: Baseline Projection for N.A. Plastic Composite Content



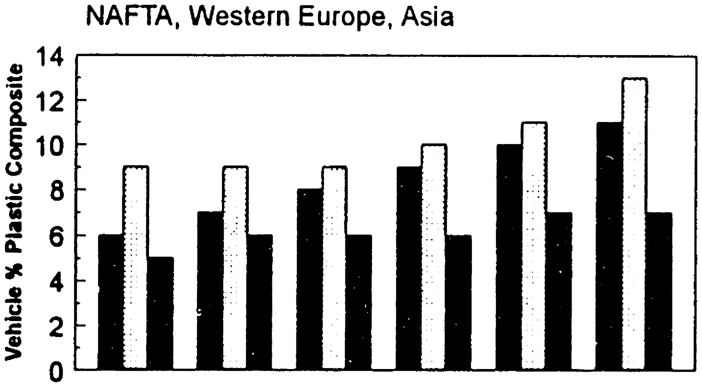
		1995	2000	2005	2010	2015
Exterior	▨	74.9	84.8	100.2	111.6	122.8
Interior	☐	88.6	94.8	97.0	98.8	102.0
Under the Hood	▨	25.8	30.8	36.4	38.8	41.9
Structural	■	1.4	1.5	4.3	10.2	18.5
Other	☐	31.5	34.8	36.7	37.8	38.0

Figure 2.9: Baseline Projection of Plastic / Vehicle Until 2015



Lbs / Vehicle	1990	1995	2000	2005	2010	2015
NAFTA ■	184	223	247	275	299	324
Western Europe □	200	209	220	242	266	293
Asia ■	138	167	172	177	183	188

Figure 2.10: Baseline Projection of Percentage Plastic in Vehicles Until 2015



	1990	1995	2000	2005	2010	2015
NAFTA ■	6	7	8	9	10	11
Western Europe □	9	9	9	10	11	13
Asia ■	5	6	6	6	7	7

Chapter 3: Rationale for Scenarios

3.1 TOOL FOR PLASTIC COMPOSITE SUPPLIERS AND DESIGNERS

The baseline case, outlined in chapter 2 of this thesis, constitutes an individual, parts-driven methodology for projecting regional and global automotive plastic composite content in the absence of major discontinuities. It is important to forecast likely evolutionary growth as many strategic decisions, such as the addition and location of production capacity, are made on the basis of this information. However, major discontinuities do occur, some totally unpredictable and several that might be anticipated. Indications of many future changes are both visible long before the change occurs and may be susceptible to influence from major interest groups.

For example, future environmental regulation may be understood from the priorities of the electorate, the studies of scientists, and the economic concerns of industry. It is unusual for any legislation to be enacted that will have a major impact on industry without a foreshadowing period of debate and proposed legislation. Similarly, many technological changes can be anticipated in the automotive materials industry. Overcoming major obstacles to economic processing and redesigning applications around a material's strengths are priorities of several materials suppliers. The impact of the introduction of new designs or improved processes is difficult to quantify, but technical cost models are helpful in determining approximate costs of production for new processes or designs.

This scenario analysis is meant to form a dynamic framework from which to set an automotive material supplier's long term priorities in order to make suitable commitments and choices. This tool can give decision makers a way to reasonably assess the potential impacts of various legislative or technological discontinuities. In addition, this methodology can be useful as a prioritization tool, in order to determine the best path by which to attempt to influence future changes. Prioritization may be especially relevant for the participation of glass fiber and resin suppliers in the fiercely competitive automotive industry, as the composite industry is well behind the steel and aluminum industries in terms of design familiarity and committed resources.

3.2 SCENARIOS SELECTED

The scenarios considered in this analysis are those that represent the largest realistic opportunities for increased volume for composite automotive suppliers and those that represent the composite industry losing the most volume from the basecase projection. Two scenarios are considered that are external to the composite industry, both involving changes in environmental regulation. Additionally, two scenarios internal to the composite industry, involving revolutionary and incremental technological advances, are analyzed. Figure 3.1 depicts the manner in which the scenarios impact the performance and cost attributes of automotive material substitution.

The first external scenario, developed in detail in chapter four of this thesis, addresses regional recycling concerns in North America, Western Europe, and Asia. In general, tightened recycling policies have a negative impact on automotive plastic composite consumption as recycling infrastructure is primarily organized around ferrous materials, and the plastic composite parts become automotive shredder residue (ASR) which is not currently recycled. The regional scenarios are built around the classification of ASR as hazardous waste, the banning of SMC as an automotive material, and the implementation of aggressive limits to unrecycled materials in automobiles. Although it is expected that tightened recycling legislation will have a negative impact on plastic composite consumption in automotive applications, this analysis attempts to quantify the potential level of that impact under various proposed legislations.

The second external scenario, developed in chapter five, involves the adoption of stricter fuel economy standards, which, in turn, are assumed to increase automakers' willingness to pay for weight savings. In the United States, Corporate Average Fuel Economy (CAFE) legislation has been in existence since the oil crisis in the late 1970s but efficiency requirements have not increased since 1990. Environmental concern or national security concerns could spark a new government to enact stricter legislation. In Europe and Asia, voluntary action by the automotive producers, in response to customer concerns, has led to the adoption of goals to reduce CO_2 levels. A direct method of reducing automotive CO_2 emissions is to increase fuel efficiency. As in the North American case, it is assumed that a portion of increased fuel efficiency is achieved through reducing the weight of the average vehicle, and that automakers would be willing to pay a premium for this weight savings.

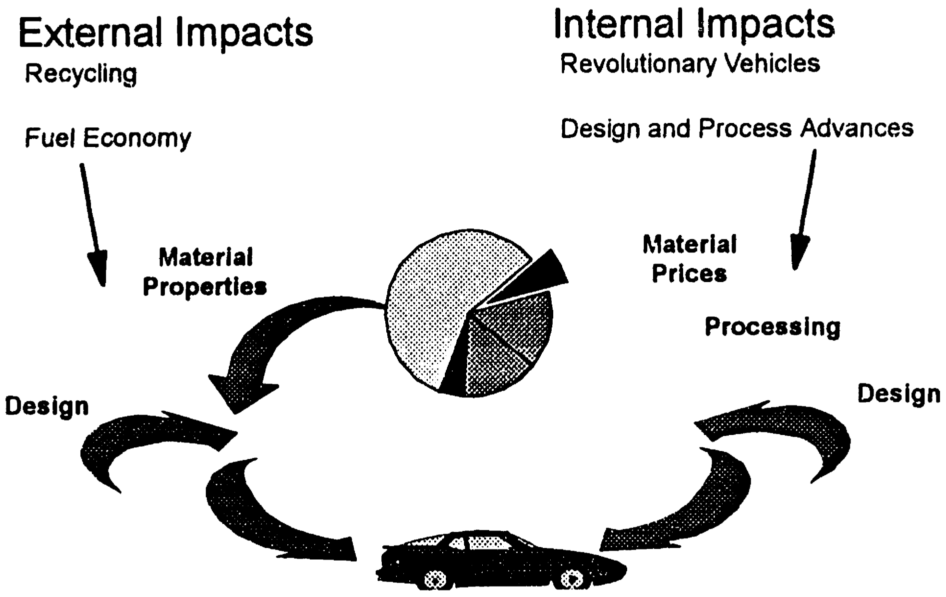
The first scenario which involves changes internal to the composite industry is developed in chapter six. This scenario involves the design of a commercially viable vehicle in which all the structural components of the vehicle (the body-in-white) are made of plastic composite. Currently, composite body-in-whites (BIWs) are only produced in small batch quantities for the racing industry and for prototypes of electric vehicles or other alternative, light weight vehicles. Some structural components are manufactured for the automotive industry, but, without significant parts consolidation, are generally only economical at production volumes of under 20,000 parts per year. In this scenario, the production cost of part of a composite intensive vehicle (CIV) prototype, designed by Ford Motor Company, is compared against the production cost of a similar functional system in steel. Carbon fiber reinforced vehicles were not considered in this scenario analysis since: 1) few prototype vehicles exist of a carbon fiber passenger vehicle, 2) it would take a dramatic discontinuity to push carbon fiber prices low enough ($3 / lb to $5 / lb) for economical manufacturing, and, 3) given the current obstacles, any advances that occur are unlikely to have significant commercial impact within the 20 year horizon under consideration. The impact of this revolutionary vehicle development is considered to be global.

The final scenario, developed in chapter seven, examines the impact of incremental design, manufacturing, and process advances on plastic composite system penetration. Designing automotive systems around the strengths of composites, rather than the incumbent steel, can lead to substantial cost savings over steel systems at low production volumes. Traditionally, composites have benefited from cost advantages only through lower tooling costs than steel; however, when designing one composite part in the place of several steel parts, plastic composites can also derive cost advantages by avoiding assembly costs. In addition to design advances, resin advances could result in cost advantages over steel systems at higher production volumes if cycle times for Resin Transfer Molded (RTM) parts can be decreased. Lastly, advances in glass fiber preform technology for the RTM process could make the RTM process more economical at higher production volumes by enabling a reduction in reinforcement material costs. Although different design examples might be more appropriate for Europe or Japan than the ones chosen for this scenario, the impact of incremental design and manufacturing advances is assumed to be similar globally.

3.3 EXTERNAL FACTORS NOT CONSIDERED

No additional cost advances for steel or aluminum have been considered in these scenarios. Steel advances are not considered in the basecase or in the existing scenarios because cost characteristics for composites are assessed through comparison with the current practices reflected in the MSL steel stamping and assembly cost models. Scenarios could be created where steel achieves the advances outlined in the Ultra Light Steel Auto Body (ULSAB) studies. Such analysis has not been attempted in this thesis. In addition, obstacles to displacement of the incumbent material, such as sunk capital in steel facilities, opposition from metal worker unions, and automotive designer unfamiliarity with composites, have not been incorporated into this analysis.

Figure 3.1: Scenario Overview



Chapter 4: Scenario A: Tightened Recycling Legislation in the US, Europe, and Japan

Aggressive and moderate possibilities for changes in recycling legislation and economics are proposed for the US (proxy for the NAFTA region), for Western Europe, and for Japan (proxy for Asia). All scenarios are based on either proposals that are currently being debated or draft legislation. The potential impacts of these legislative changes on polymer consumption in automotive applications are assessed through prioritization of recycling options and through the dampening of projected substitutions based on logistic curves.

4.1 UNITED STATES

4.1.1 Overview of Current Legislation:

There is currently no federal legislation on recycling that applies to the automotive industry. The only current state legislation in the U.S. is in California, where Automotive Shredder Residue (ASR) is classified as hazardous waste.[8]

4.1.2 Aggressive Recycling Legislation Scenario:

In this aggressive scenario, we consider both that the California law on hazardous waste is adopted federally by 2005 (i.e. all ASR is classified as hazardous waste) and that SMC is banned as an automotive material due to its poor recycling potential relative to steel, aluminum, or thermoplastics. The potential timeframe of legislation is the year 2005.

Landfill costs for non-hazardous material in the United States are currently $33 / tonne. For hazardous waste, it is assumed that landfill costs will be $100 / tonne due to more expensive precautions to isolate this material from the groundwater system.

4.1.3 Potential Impacts of Aggressive Recycling Legislation:

The implications of this scenario will include: increased landfill costs for ASR, increased prices of automobiles, pressure from consumers for auto manufacturers to lessen ASR or eliminate those components which result in a hazardous classification, decrease in substitution of optional plastic substitutions which end up in ASR, and the elimination of SMC from automotive market. Quantifying the SMC impact is straightforward. In 1995, there were 192 million lbs of SMC used in the North American fleet, corresponding to 14.5 pounds per vehicle. The growth projection for these parts result in a base case of approximately 275 million lbs of SMC used by 2005, 410 million lbs by 2010, and 560 million lbs by 2015. In this aggressive scenario, all SMC will be eliminated from future plastic automotive consumption.

Quantifying the impact of hazardous ASR classification is more ambiguous. Here two main impacts are assumed: 1) substitution or elimination of easily replaced polymer and plastic composite parts, and 2) the dampening of future plastic composite substitution opportunities. First, as manufacturers are pressured to find ways to lessen ASR, we assume that designers will find ways to trim interior applications and the amount of interior plastics will decrease by 10% from 102 lb per vehicle to 92 lb per vehicle by 2015. As well, all closures will revert to steel or aluminum, decreasing body panel plastic composite consumption by 100% from 29 pounds per vehicle to zero pounds per vehicle by 2015. As all SMC has already been accounted for, the net reduction in polymer consumption from closures reverting to metal would be 7 pounds per vehicle. Second, as landfill costs become a more significant part of the component cost, substitutions (listed in table 2.2) that were classified as type 1 will transform to type 7, and those that are classified as type 2 or type 3 will no longer be viable. (See sections 1.4 and 2.4.2 for a thorough explanation of substitution curves used in this analysis). Given that SMC has already been eliminated, this substitution dampening will reduce polymer consumption by an additional 42.5 pounds per vehicle by 2015. Hence, the overall impact is a decrease of 88 pounds per vehicle from the base case of 324 pounds per vehicle to the aggressive recycling scenario of 236 pounds per vehicle in 2015.

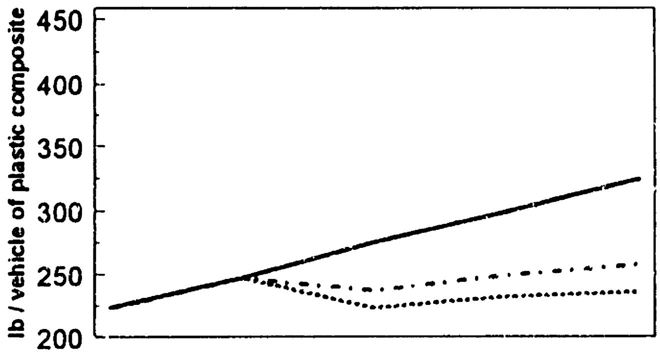
4.1.4 Moderate Recycling Legislation Scenario:

Legislation is implemented that puts responsibility for the treatment of ASR onto automakers. Pyrolysis of ASR followed by landfill of solid waste is an acceptable treatment. See Section 4.2.2 for discussion of ASR recycling options.

4.1.5 Potential Impacts of Moderate Recycling Legislation:

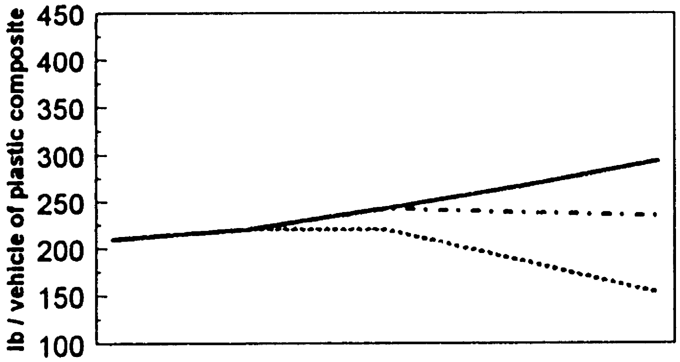
The cost of treating ASR is added onto component cost, resulting in damping of substitution dynamics. As in the aggressive scenario, substitutions that were classified as type 1 will transform to type 7, and those that are classified as type 2 or type 3 will no longer be viable. This will reduce plastic composite consumption by a total of 66 pounds per vehicle by 2015.

Figure 4.1: N.A. Scenarios on Recycling Legislation


Projected Plastic Composite Content in Average N.A. Vehicle

Year	1995	2000	2005	2010	2015
Baseline —	223	247	275	299	324
Aggressive ····	223	247	223	232	236
Moderate - ·	223	247	237	249	258

Figure 4.2: Western European Scenarios on Recycling


Projected Plastic Composite Content of Average Western European Vehicle

Year	1995	2000	2005	2010	2015
Baseline —	209	220	242	266	293
Aggressive ····	209	220	220	187	153
Moderate - ·	209	220	242	238	234

4.2 WESTERN EUROPE

4.2.1 Overview of Current Legislative Proposals:

The European Community currently endorses the following voluntary targets. After 2002, each manufacturer should ensure a maximum of 15% by weight of the average car is landfilled or incinerated without energy recovery. For new models, the target is a 10% by weight maximum. After 2015, each manufacturer should ensure a maximum of 5% by weight of the average car is landfilled or incinerated without energy recovery.[9]

Various automotive manufacturers and the German government are refining the proposed definition of recycling for the adoption of the EU voluntary regulations listed above. There is a significant group who believes that incineration with energy recovery should not be classified as true material recycling but rather as "energy recycling."[10] The classification of incineration with energy recovery and the realism of a 95% target for recycled automotive materials are both currently under debate.[11]

4.2.2 Discussion of Recycling Options:

To determine the effect on plastics of this legislation, the relative economics of plastic composite recycling (including dismantling, ASR pyrolysis, quaternary ASR recycling, ASR mechanical separation and selective precipitation, and landfilling) as well as glass recycling, primary and secondary rubber recycling, recycling of fabric, leather, and wood, and materials substitution were examined. Options can be divided into those that require separation before shredding, and those that require only a change in the handling of Automotive Shredder Residue (ASR). Dismantling, which is the physical separation of parts before shredding, can be economically applied to about 30% of the nonferrous metal content of an automobile[12], and to the wheels. There is not enough value in the plastic composite parts to warrant dismantling given current manufacturing practices.[13] As the tires are taken off with the wheels, no extra value needs to be inherent in the tires for them to be dismantled. Rubber tires have traditionally been landfilled, but many efforts have been underway in recent years to reuse or recycle automotive tires. In Germany, tires are ground up and used as an additive in concrete, which is secondary rubber recycling.[14] A primary rubber recycling option has been developed recently by National Rubber in Toronto, Canada.[15] This technology allows for the sulpher bonds to be broken through mechanical mixing in an oxygen depleted environment and for the rubber to be revulcanized into a new application. Given high landfill costs, this primary or secondary rubber recycling option appears to provide an economical way to recycle a fraction of tires, limited by secondary applications available and the amount of recycled rubber that could be reintroduced into closed loop applications without degrading quality. Last among the dismantling options, when higher recycled content is required, glass can be dismantled and recycled with a minimal cost penalty.[16]

Options that require only a change in handling of ASR are attractive because they require less of an infrastructure change. Currently, the vast majority of ASR is landfilled. Options to reduce the volume of ASR that is landfilled include ASR pyrolysis, quaternary ASR recycling, and ASR mechanical separation and selective precipitation. ASR pyrolysis is the thermal transformation of organic waste into oil, gas, and solid waste. When tipping fees are over $50 per tonne, this option, in conjunction with hulk shredding and landfilling of the solid waste, is the most feasible in terms of cost, required infrastructure and reliability of the process.[17] ASR mechanical separation and selective precipitation, a process developed at the Argonne National Laboratory where polyurethane foam and inorganic fines are mechanically separated from the dried ASR and thermoplastics are selectively precipitated out of the remaining portion of the ASR through use of a hot solvent, is even more cost effective than ASR pyrolysis.[18] However, the process is still at the laboratory stage whereas the economics of ASR pyrolysis are well understood. ASR incineration with energy recovery (quaternary ASR recycling) is another economical option where this option is considered materials recycling. Lastly, if the part can be substituted and recycling is an expensive or infeasible option, materials substitution (i.e. part-by-part replacement of a material used in an automotive application) will occur.

4.2.3 Aggressive Recycling Legislation Scenario:

In this scenario, it is assumed that all EC voluntary measures become mandatory. It is also assumed that a minimum of tertiary recycling (e.g. pyrolysis) is required: hence, incineration with energy recovery is not classified as recycling in this scenario. Germany's landfill cost remains at approximately 150 DM / tonne, which converts to approximately $88 / tonne. At this landfill cost, the option of hulk shredding followed by pyrolysis and landfill of the solid wastes is more profitable than the straight landfill option,[19] so ASR will be treated and only 28% of plastics used in vehicles will have to be landfilled as solid waste from pyrolysis. Other aggressive recycling scenario assumptions include: 1) that an additional 30% of waste rubber from tires can be absorbed by National Rubber technology for primary or secondary recycling, beyond the 40% of rubber that is currently used in cement making in Germany, 2) glass can be recycled more economically than landfilling pyrolysis solids, 3) the "other" category, which includes leather, fabrics and wood, cannot be recycled without incineration, so as much as possible is substituted, and 4) all other unrecycled material reductions comes from substituting metal for plastic.

4.2.4 Potential Impacts of Aggressive Recycling Legislation:

The material content, recycled percent, and possibilities for substitution in a typical European car are used as a starting point in order to assess the impacts of this scenario. Currently, 22.7% of the average German vehicle is not recycled. Of this 22.7%, the relevant unrecycled materials are shown in Table 4.1.

Material	Percent in Vehicle	Percent Not Recycled	Contribution to Unrecycled
Plastic	10%	100%	10%
Rubber	7%	60%	4.2%
Glass	4%	100%	4%
Non-Ferrous Metal	5%	10%	.5%
Other	4%	100%	4%
			22.7%

Table 4.1: Unrecycled Materials in the Average German Vehicle

In order to reach the 15% target for average vehicles in 2002, 7.7% of unrecycled material must either be eliminated, recycled, or replaced with a recyclable substitute. Given the assumptions made in the aggressive scenario, an extra 30% of the rubber will be recycled into new rubber parts and the remaining recycled content required will be reached through pyrolysis of the ASR with landfill of the solid waste from pyrolysis. Plastic composite consumption in the average vehicle is unlikely to experience any growth beyond 10% of the vehicle due to these recycled content pressures.

Material	Percent in Vehicle	Percent Not Recycled	Contribution to Unrecycled
Plastic	10%	28%	2.8%
Rubber	7%	30%	2.1%
Glass	4%	100%	4%
Non-Ferrous Metal	5%	10%	.5%
Other	4%	100%	4%
			15%

Table 4.2: Unrecycled Material Target for the Average German Vehicle by 2002

Additional efforts will have to be made to reach the 10% unrecycled material target for new vehicle models in Germany by 2002. Recycling of the 4% glass content of each vehicle is the next step, in conjunction with the recycling of the 0.5% nonferrous metal content that is currently not recycled. Table 4.3 shows those materials still contributing to unrecycled content in the new vehicle models in 2002. Just as for the average vehicle, plastic composite consumption in the new vehicle models is unlikely to experience any growth beyond 10% of the vehicle due to these recycled content pressures.

Material	Percent in Vehicle	Percent Not Recycled	Contribution to Unrecycled
Plastic	10%	28%	2.8%
Rubber	7%	30%	2.1%
Glass	4%	0%	0%
Non-Ferrous Metal	5%	0%	0%
Other	3.6%	100%	3.6%
			10%

Table 4.3: Unrecycled Material Target for New Vehicle Models in Germany by 2002

In reaching for the 5% unrecycled material target for 2015, a reduction in the plastic composite content will be required, given the assumptions of the aggressive scenario. First, the "other" category (wood, leather, fabrics) will be reduced as much as possible through substitution by materials that can be more easily recycled. Then, substitution of plastic composite parts by fully recyclable materials will occur until the target of 5% of unrecycled materials is met. The remaining plastic composite content of the vehicle will still undergo pyrolysis and landfill of the waste solids. Hence, 3.2% of the vehicles' plastic weight must be eliminated and all growth in plastics consumption must be halted. Thus, the total impact on plastics would be the elimination of 140 pounds per vehicle from the 2015 base case, resulting in an average vehicle plastic composition of 153 pounds per vehicle.

Material	Percent in Vehicle	Percent Not Recycled	Contribution to Unrecycled
Plastic	6.8%	28%	1.9%
Rubber	7%	30%	2.1%
Glass	4%	0%	0%
Non-Ferrous Metal	5%	0%	0%
Other	1%	100%	1%
			5%

Table 4.4: Unrecycled Material Target for the Average German Vehicle by 2015: Aggressive Scenario

4.2.5 Moderate Recycling Legislation Scenario:

This scenario is moderate in terms of its impact on automotive plastic composite consumption in Western Europe. In this scenario, we will assume that all European Community voluntary measures become enforced. Incineration with energy recovery is classified as recycling in this scenario. Landfill costs go up to $200 / tonne, sparking interest in new recycling infrastructure. As in the aggressive scenario, 70% of rubber tires can be absorbed due to current cement usage and National Rubber primary recycling technology.

4.2.6 Potential Impacts of Moderate Recycling Legislation:

Given landfill costs of $200 / tonne, the option of hulk shredding followed by ASR pyrolysis and landfill is economically very attractive and straight landfill is a money losing option. [20] Under moderate scenario conditions, no impact will be felt by plastic composite suppliers until 2005, when a slowdown in substitution of plastics will occur from 2005 to 2015 due to target constraints. Thus, the total impact on plastic composites would be elimination from the baseline of 2.6% of the vehicle's weight in plastic content, resulting in an average plastic composite composition of 234 pounds per vehicle. (see figure 4.2)

Material	Percent in Vehicle	Percent Not Recycled	Contribution to Unrecycled
Plastic	10.4%	28%	2.9%
Rubber	7%	30%	2.1%
Glass	4%	0%	0%
Non-Ferrous Metal	5%	0%	0%
Other	4%	0%	0%
			5%

Table 4.5: Unrecycled Material Target for the Average German Vehicle by 2015: Moderate Scenario

4.3 JAPAN

4.3.1 Overview of Current Legislation:

Japan's Industrial Structural Council currently endorses voluntary targets as follows:[21]

1) By 2002, each manufacturer should ensure that from 75% to 85% of a typical vehicle is recycled

2) After 2002, each manufacturer should ensure a usage of materials and specifications that will allow at least 90% by weight of all new models can be recycled

3) By 2015, each manufacturer should ensure 95% by weight of all new models are recycled

The Japanese government intends to conduct surveys on attainment levels each year; and, if progress is slow, the government plans to introduce enforceable legislation. It is unknown if incineration with or without energy recovery is defined as recycling under this legislation.

4.3.2 Aggressive Recycling Legislation Scenario:

In this scenario, we will assume that all Japanese voluntary measures become enforced. We will also assume that tertiary recycling is required at a minimum. Hence, incineration with energy recovery is not classified as recycling in this scenario.

4.3.3 Potential Impacts of Aggressive Recycling Legislation:

As landfilling costs are in the range of $80 to $100 per tonne and 5% of the vehicle is exempt from recycling legislation in both Japan and Germany, plastics consumption is capped at the same levels as in the Western European scenario. However, as the current level of automotive plastic composite consumption in Japan is far lower than in Germany (see figure 2.10), only a slight decrease in plastic composite consumption from 7% of the average vehicle to 6.8% of the average vehicle will occur under these aggressive scenario conditions. Thus a minimal impact of a 5 pounds per vehicle reduction in plastic composites is felt in the aggressive scenario.

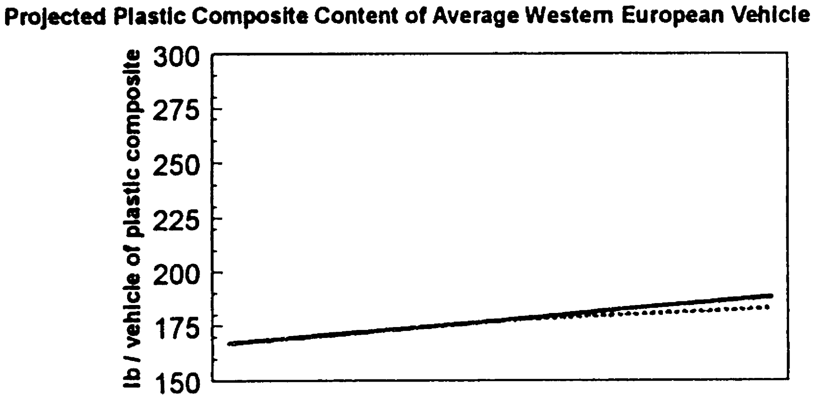
4.3.4 Moderate Recycling Legislation Scenario:

In this scenario, we will assume that all Japanese voluntary measures become enforced. Incineration with energy recovery is classified as recycling in this scenario.

4.3.5 Potential Impacts of Moderate Recycling Legislation:

Under the moderate recycling scenario conditions, there will be no impact on plastic composite consumption as projected growth of plastic composites in Asian vehicles is less the amount that could be absorbed under this recycling legislation.

Figure 4.3: Asian Scenarios on Recycling



Year	1995	2000	2005	2010	2015
Baseline —	167	172	177	183	188
Aggressive ····	167	172	177	180	183
Moderate - ·	167	172	177	183	188

Chapter 5: Scenario B: Legislation that Results in Increased Fuel Economy

In this chapter, aggressive and moderate possibilities for changes in fuel economy legislation are proposed for the US (proxy for the NAFTA region), for Western Europe, and for Japan (proxy for Asia). The scenarios are based on draft legislation, on proposals that are currently being debated, and on the tightening of current legislation. The potential impacts of these tightened fuel economy scenarios on polymer consumption in automotive applications are assessed.

5.1 UNITED STATES

5.1.1 Overview of Current Legislation:

The current fuel economy legislation is referred to as Corporate Average Fuel Economy (CAFE) requirements and governs the minimum average fuel economy of an automotive manufacturer's domestic fleet. From 1990 to 1997, CAFE requirements have remained level at 27.5 miles per gallon (mpg). Historical CAFE requirements and automotive manufacturer's compliance are shown in Figure 5.1. CAFE requirements have remained stagnant for the last 7 years largely due to pressure on the US government from both domestic and foreign automotive manufacturers. Domestic automotive manufacturers have agreed to participate in such projects as the Project for a New Generation of Vehicles (PNGV), which aims to economically produce a vehicle that obtains 80 mpg, and alternative fuel vehicle projects as a compromise deal with the US government.

Although it is highly unlikely that PNGV targets for conventional vehicles can be met by 2015, electric vehicles are being developed that will likely be able to satisfactorily meet the 10% zero emission standards California, Massachusetts, New York, and British Columbia are planning on implementing by 2015.[22] As electric vehicles do not fit into the CAFE framework, and as they only eliminate emissions locally, they are not incorporated into the fuel economy analysis. However, the incremental plastic content above an average vehicle is accounted for in the total pounds per vehicle calculations in this scenario. Cost driven potential impacts of alternative vehicles are assessed in chapter 6 of this thesis.

5.1.2 Aggressive Fuel Economy Legislation Scenario:

There are three major assumptions in the North American aggressive fuel economy legislation scenario. First, CAFE increases to 35 mpg by 2015. Second, Zero Emmission Vehicles (ZEVs) account for 2% of the total vehicle fleet and plastic composite monocoque BIWs are employed for 50% of the ZEVs. Lastly, it is assumed that 50% of lightweighting occurs by plastic substitution for steel and the remaining lightweighting occurs by aluminum substitution for steel.

5.1.3 Potential Impacts of Aggressive CAFE Legislation:

CAFE is imposed at 35 mpg for 2015 domestic automotive production. Hence, the additional requirement would call for a 7.5 mpg CAFE increase, which could be achieved by a number of methods, including: drivetrain efficiencies, lightweighting, aerodynamics, friction reduction, and improved traffic infrastructure. Assuming that lightweighting will account for 35% of the remaining imposed CAFE increase, 2.63 mpg must be achieved through lightweighting of vehicles. Studies have shown that for 300 pounds of weight saved per vehicle, an additional 2 mpg of fuel economy will be achieved[23] Under that rule, an average increase of 131 pounds per vehicle of plastic composite would occur by 2015 due to lightweighting if 50% of lightweight substitution was plastic for steel. The assumption of 1 lb plastic for every 1.5 lb steel replaced is used[24] In addition, an incremental increase of 3 pounds per vehicle of plastic composite would occur if plastic composite monocoques of 300 pounds per vehicle are assumed for 50% of electric vehicles in 2015.

5.1.4 Moderate Fuel Economy Legislation Scenario

In the North American Moderate Fuel Economy Legislation Scenario, CAFE regulations are assumed to increase to 30 mpg by 2015. As in the aggressive scenario, ZEVs account for 2% of the total vehicle fleet and plastic composite monocoque BIWs are employed for 50% of the ZEVs. The assumption is again made that 50% of lightweighting occurs by plastic substitution for steel and the remaining lightweighting occurs by aluminum substitution for steel.

5.1.5 Potential Impacts of Moderate CAFE Legislation:

Under moderate scenario conditions, a total increase of 47 pounds per vehicle would occur by the year 2015.

Figure 5.1: Assumptions for NA Fuel Economy Scenarios

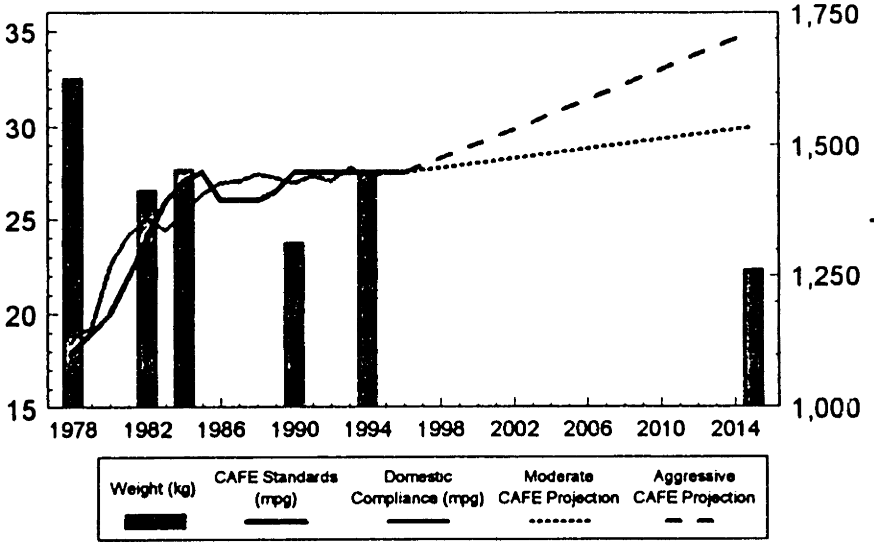
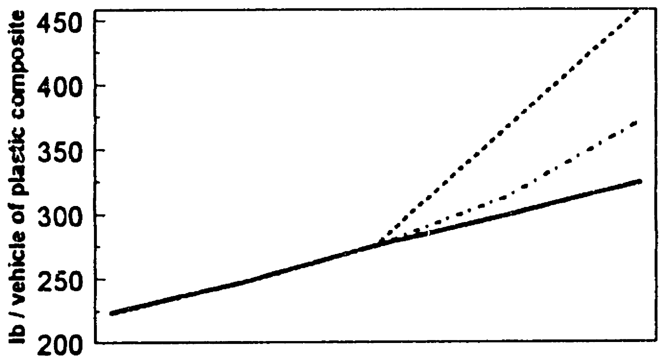


Figure 5.2: N.A. Scenarios on Fuel Economy Increases

Projected Plastic Composite Content of Average North American Vehicle



Year	1995	2000	2005	2010	2015
Baseline —	223	247	275	299	324
Aggressive ····	223	247	275	366	458
Moderate ···	223	247	275	313	371

5.2 WESTERN EUROPE

5.2.1 Overview of Current Legislation:

Currently, legislation for CO_2 emission reductions exists in Scandinavia and similar legislative proposals are being considered in Germany.[25] Germany already levies environmental taxes of up to 300% on automotive fuel.

5.2.2 Aggressive Fuel Economy Legislation Scenario:

The major assumptions in the Western European Aggressive Fuel Economy Legislation Scenario are as follows. First, it is assumed that legislation introduced to enable the reduction of CO_2 emissions by 25% by 2015 translates into targets for a 10% increase in average fuel efficiency by 2015. Secondly, it is assumed that the current average fuel efficiency in Western Europe is 26.5[26] mpg, hence the anticipated average increase in fuel efficiency is 2.7 mpg. Lastly, it is assumed that 50% of lightweighting occurs by plastic substitution for steel and the remaining lightweighting occurs by aluminum substitution for steel.

5.2.3 Potential Impacts of Aggressive Fuel Economy Legislation:

Assuming 35% of required fuel efficiency increases are accounted for by lightweighting, average fuel efficiency increases of 2.7 mpg by 2015 translate into the need for a 0.95 mpg average increase due to lightweighting by the year 2015. According to the same assumptions used in section 1.1.3, a 0.95 mpg increase by lightweighting would translate into 47 additional pounds of plastic composite per vehicle.

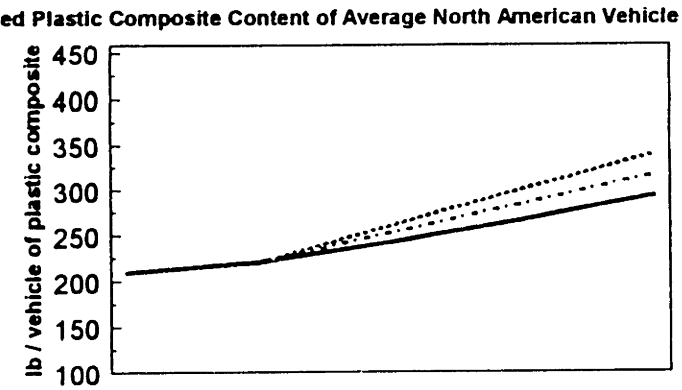
5.2.4 Moderate Fuel Economy Legislation Scenario:

In the Western European Moderate Fuel Economy Legislation Scenario, it is again assumed that targets for a 10% increase in average fuel efficiency by 2015 are met by an average increase in fuel efficiency of 2.7 mpg. In this scenario, however, the assumption is made that only 25% of European lightweighting occurs by plastic substitution for steel and the remaining lightweighting occurs by aluminum substitution for steel.

5.2.5 Potential Impacts of Moderate Fuel Economy Legislation:

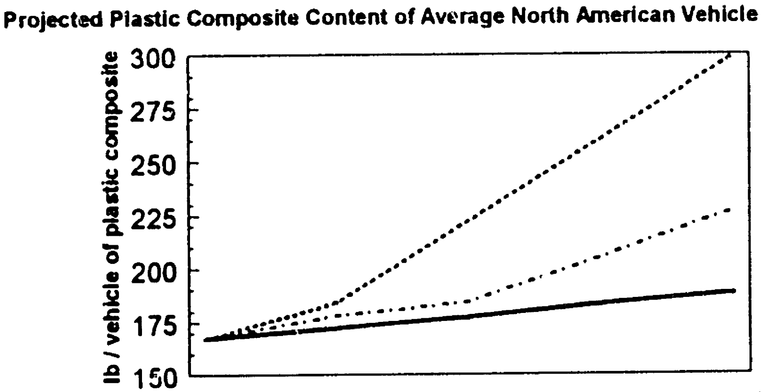
Under moderate scenario conditions, a total increase of 24 pounds per vehicle would occur by the year 2015.

Figure 5.3: Western European Fuel Economy Scenarios



Year	1995	2000	2005	2010	2015
Baseline —	209	220	242	266	293
Aggressive ····	209	220	260	300	340
Moderate ···	209	220	252	284	317

Figure 5.4: Asian Fuel Economy Scenarios



Year	1995	2000	2005	2010	2015
Baseline —	167	172	177	183	188
Aggressive ····	167	184	222	260	299
Moderate ···	167	178	184	205	227

5.3 JAPAN

5.3.1 Overview of Current Legislation:

By the year 2000, a goal has been set to reduce CO_2 emissions to the 1990 level.[27] The Japanese automotive industry has responded by developing fuel efficiency technology which will increase the average fuel efficiency by approximately 8.5% by 2000.

Fuel Efficiency targets for various weight classes are as follows:[28]

	Standard	Small	Mini
Weight (kg)	less than 1515.5	827.5 - 1515.5	less than 827.5
Weight (lbs)	less than 3334	1821 - 3334	less than 1821
1990 (k/l)	8.3	12.1	17.3
1990 (mpg)	19.7	28.7	41.1
2000 (k/l)	9.1	13	19
2000 (mpg)	21.6	30.9	45.1
Improvement by 2000	9.6%	7.4%	6.7%

Table 5.1: Japanese Fuel Efficiency Targets for 2000

5.3.2 Aggressive Fuel Economy Legislation Scenario:

There are three major assumptions in the Japanese aggressive fuel economy legislation scenario. First, current targets for the year 2000 are assumed to be achieved. Second, it is assumed that fuel economy increases an additional 15% across the fleet by 2015, translating into an additional average increase of 4.6 mpg. Finally, 60% of lightweighting is assumed to occur by plastic substitution for steel and the remaining 40% of lightweighting is assumed to occur by aluminum substitution for steel.

5.3.3 Potential Impacts of Aggressive Fuel Economy Legislation:

Assuming 35% of required fuel efficiency increases are accounted for by lightweighting, average fuel efficiency increases of 2.2 mpg by 2000 and an additional 4.6 mpg by 2015 translate into the need for a 0.77 mpg average increase due to lightweighting by the year 2000 and an additional 1.6 mpg average increase due to lightweighting by the year 2015. Given that 60% of lightweighting is assumed to be accomplished through plastic substitution for steel, a 0.77 mpg increase by lightweighting would translate into 46 more pounds of plastic composite per vehicle in the year 2000 than in 1990. This would result in an increase of 14 pounds per vehicle over the basecase scenario. Likewise, a 1.6 mpg increase by lightweighting from the year 2000 to the year 2015 would translate into 97 additional pounds of plastic composite per vehicle by the year 2015. Thus, under aggressive scenario conditions, a total increase over the base case of 111 pounds per vehicle would occur by the year 2015.

5.3.4 Moderate Fuel Economy Legislation Scenario

In the moderate Asian fuel economy scenario, it is assumed that current targets for the year 2000 are not met until 2005. Additional fuel economy increases of only 5% is assumed across the fleet by 2015, translating into an additional average fuel efficiency increase of 1.5 mpg. As in the aggressive scenario, 60% of lightweighting is assumed to occur by plastic substitution for steel and the remaining 40% of lightweighting is assumed to occur by aluminum substitution for steel.

5.3.5 Potential Impacts of Moderate Fuel Economy Legislation:

Under moderate scenario conditions, the increase of 46 pounds per vehicle over the 1990 level of plastic composite content would occur by the year 2005, resulting in only 7 lb/vehicle over the basecase. An additional increase of 32 pounds per vehicle would occur by 2015, for a total increase of 39 pounds per vehicle of plastic composite above the basecase scenario.

Chapter 6: Scenario C: Revolutionary Composite Vehicles

6.1 COMPOSITE INTENSIVE VEHICLE

6.1.1 Overview of Past Research and Advances

Potential for weight reduction, NVH reduction, improved corrosion and dent resistance, and cost reduction through parts consolidation have led automotive companies to investigate the feasibility of mass producing a composite Body In White (BIW).[29] In 1988, Ford, GM, and Chrysler formed the Automotive Composite Consortium (ACC), with the purpose of developing technologies for structural plastic composite use in primary vehicle structures. An ACC project (Focal Project I) created a RTM front-end prototype that replaced the entire steel front-end of the 1984 Ford Escort. This front-end, made of vinyl ester, 2 foam cores, triaxially braided glass fiber, and continuous strand mat, met or exceeded all performance measures of the steel system and reduced the system weight by 25%.[30] Ford has extended this work, designing and prototyping a 7 piece, composite, monocoque, BIW. This Composite Intensive Vehicle (CIV), which closely resembles the steel Honda Odyssey minivan in functionality, is mainly constructed of Fiberglas reinforced vinyl ester RTM parts with an SMC outer roof panel. The vehicle was designed to take advantage of parts consolidation, design-in stiffness (e.g. corrogated parts), and off-site modular assembly.

6.1.2 Technical Cost Modeling of CIV

Paul Kang of the Materials System's Laboratory at MIT has created a flexible RTM technical-economic cost model to evaluate the cost of the CIV relative to the cost of the 1995 steel Honda Odyssey. The steel stamping and assembly costs are calculated using the MSL steel stamping and assembly models[31] [32] The stamping and assembly of the 36 parts of the steel front-end of the Odyssey have been analyzed and compared to the fabrication and assembly of the two RTM CIV parts. The CIV front end system is economically competitive at production volumes up to 60,000 parts per year, as shown in figure 6.1. Key inputs and a summary of key variables are included in table 6.1 below.

	Number of Laborers / Stream	**Cycle Time (minutes)**	**Number of Parallel Streams @ 100,000 PV**
Fiber Cutting	1	0.7	2
Thermoforming	1	3.6	3
Preform Trimming	1	0.7	2
F.C. Molding	1	0.9	1
F.C. Post Cure	0.5	15	13
F.C. Trimming	0.5	0.5	1
Preform Assembly	0.5	0.7	1
RTM Molding	1.5	47	19
Inspection / Trimming	1	0.7	1

Table 6.1: Key Variables in Basecase CIV Front-End System Cost Modeling

6.2 LIGHTWEIGHTING MATERIAL OPTIONS FOR REVOLUTIONARY VEHICLE

At the same time that evolutionary and revolutionary advances may be occurring for plastic composite vehicles, they also may be occurring for aluminum vehicles and for the incumbent steel vehicles. The aluminum industry, in conjunction with automotive partners, is refining the Aluminum Intensive Vehicle (AIV) and the Audi A8. The AIV is a conventional aluminum unibody design which offers a 20% weight savings over steel for a $600 manufacturing cost premium at production volumes of 220,000 vehicles / year.[33] With redesign of the unibody BIW, Alcan believes that they can achieve a 50% weight savings over steel at an unknown cost premium. The A8 is a spaceframe design which incorporates extruded parts and hydroformed tubes into a skeletal structure to which aluminum closures are attached. Although designed around lost cost aluminum manufacturing methods, there are more barriers to successful implementation by automakers (such as high scrap rates, new equipment investments and labor training) than with the familiar unibody design. In all of the scenarios of this thesis in which weightsaving is the driving force, it has been assumed that aluminum would account for approximately 50% of the lightweighting while plastic composites accounted for the remaining 50%. However, the interdependence of structural plastic composite penetration on aluminum is a dynamic and requires monitoring.

The steel industry has not remained passive to the assault on its dominance of automotive materials. A consortium of North American steel producers has hired Porsche Engineering Services to study the structural and economic feasibility of technology to reduce the weight of the average steel vehicle between 20% and 40%. Techniques such as tailor welded blanking, hydroforming, and laser welding and the use of high strength steels are advances that could be incorporated in a lighter weight steel vehicle if legislative pressure for light weight vehicles does materialize. Porche Engineering has released its first report, entitled Ultra Light Steel Autobody I (ULSAB I), which states that the weight of the average steel vehicle could be reduced by 20% without sacrificing any performance and at what appears to be no cost penalty. ULSAB II is currently underway to refine the ULSAB I design, and to validate the feasibility and economics of ULSAB I.

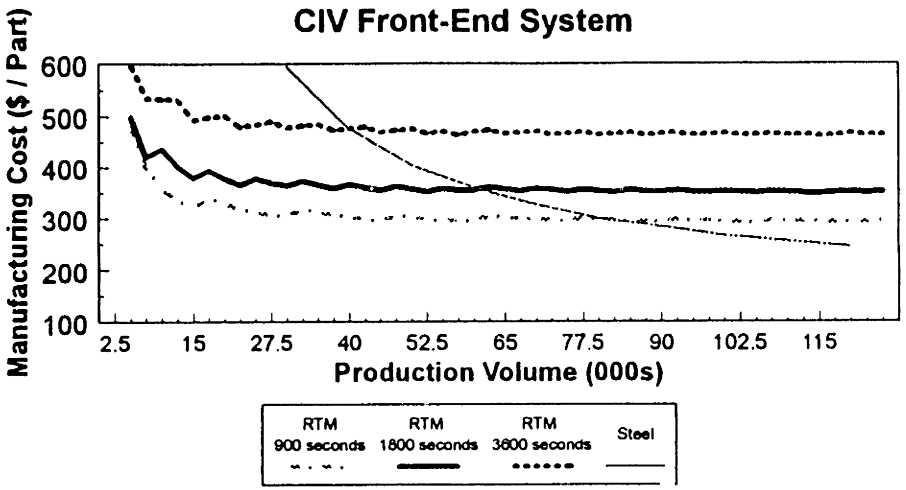
6.3 AGGRESSIVE SCENARIO FOR COMPOSITE INTENSIVE VEHICLES

It is assumed that no changes occur in the manufacturing and assembly cost positions of steel or aluminum. Additionally, the remainder of the Ford CIV is assumed to show similar cost trends to the front-end in having a cost advantage up to production volumes of 60,000 vehicles / year. Plastic composite monocoques follow a type 1 penetration curve into all vehicles of production volume under 60,000. This results in an additional 67 pounds per vehicle of plastic composite by 2015.

6.4 MODERATE SCENARIO FOR COMPOSITE INTENSIVE VEHICLES

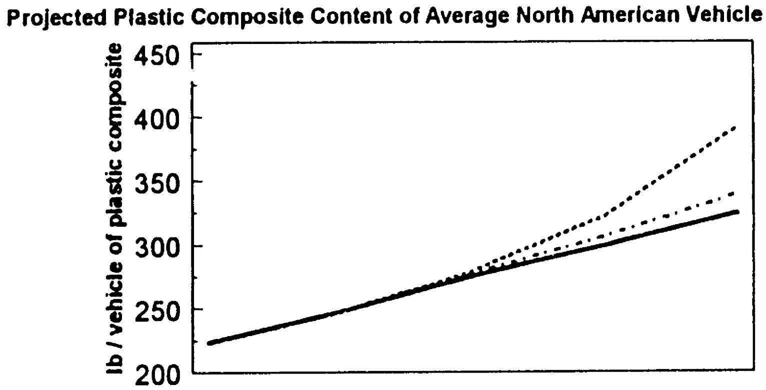
It is assumed that no changes occur in the manufacturing and assembly cost positions of steel or aluminum. Assume that only the parts of the CIV that incorporate parts consolidation (and therefore eliminate steel assembly costs) have a cost advantage up to production volumes of 60,000 vehicles per year and the other CIV parts are not competitive. Hence the front-end system and the floorpan system penetrate into all vehicles with production volumes up to 60,000 vehicles / year, with first commercial introduction in 2000 and t_0 in 2012. This results in an additional 15 pounds per vehicle by 2015.

Figure 6.1: Aggressive Scenario for Revolutionary Vehicle



Cure times of 900, 1600, and 3000 seconds
Preforms are thermoformed glass mat
Assembly cost of the two RTM halves is estimated at $20

Figure 6.2: N.A. Scenarios on Revolutionary Vehicles



Year	1995	2000	2005	2010	2015
Baseline —	223	247	275	299	324
Aggressive ····	223	247	279	322	391
Moderate ·-·	223	247	277	306	339

Chapter 7: Scenario D: Advances in Structural Composite Design and Manufacture

The advances dealt with in this chapter can be categorized into design advances, preform advances, and resin system advances. The section on design advances is relevant for all structural and semi-structural plastic composite systems. The sections on preforms and resin systems concentrate on advances for the Resin Transfer Molding (RTM) and Structural Reaction Injection Molding (S-RIM) processes. RTM, along with its close relative S-RIM, is considered by many in North America to be the process with the most potential for creating a plastic composite BIW or at least economical structural systems if breakthroughs are made in the three areas dealt with in this chapter.

7.1 DESIGN ADVANCES

7.1.1 Description

In order to design a system or an entire BIW to optimize for plastic composites, a designer needs to incorporate some of the natural advantages of composites, such as: modular assembly, parts consolidation, and extra stiffness derived from the geometry of the part. Modular assembly can provide a manufacturing cost advantage when labor costs can be reduced by enabling the assembly of a subsystem away from the automotive assembly line: the high dimensional stability of SMC has proven far better than steel in enabling modular assembly when a thin semi-structural part is involved.[34] Parts consolidation is a major driver in reducing stamping and assembly costs. As well, in parts or systems where plastic composites are not cost competitive with steel on a direct substitution basis, designs altered to incorporate added functionality (i.e. toolbox in pickup, sound deadening and insulation in floorpan) can somewhat differentiate the product. Likewise, allowing for geometrical enhancement of stiffness can make a previously noncompetitive substitute part competitive by allowing for material thickness reduction and subsequent cost reduction. The following four case studies have been chosen as representative of systems designed for composites.

7.1.2 Case Study One: Ford Taurus Integrated Front-End System

Although steel is the standard material specification for front-end systems, composite front-ends have achieved parts consolidation, weight reduction, and cost reduction for the 1996 Ford Taurus / Sable, the 1992 Dodge Viper, the 1989 Peugeot 405 and the 1984 Corvette.[35] The Ford Taurus Integrated Front-End System (IFES) demonstrates a 14% cost reduction for a platform with a production volume of 600,000 vehicles. In addition, a 22% weight reduction, and the consolidation of 22 steel parts into 2 SMC parts were obtained by Ford's IFES design team in conjunction with Budd Plastics.[36] The cost savings, which was the dominant material selection criteria,[37] was achieved through higher labor efficiency, lower overhead, less floor space requirements, fewer fixtures, and less component handling. All of these cost benefits are derived from parts consolidation and modular assembly. The SMC IFES allowed for modular assembly while a steel system did not because the SMC IFES maintained the required tolerance while the thin steel part would be susceptible to bending with handling. Many of the advantages of the Ford IFES design are considered transferable to other platforms by the Ford design team and by Budd representatives.[38] Assuming that any design barriers are overcome in order to allow the benefits of the Ford SMC IFES to be realized by other platforms, it is reasonable to model the penetration of SMC integrated front end systems into all vehicles with a Type 1 substitution curve, given the cost and lightweighting benefits achieved. It is important to note that this front end system incorporates fewer parts and far less functionality than the CIV prototype of the entire front-end system modeled in section 6.1.

7.1.3 Case Study Two: Injection Molded Thermoplastic Composite Interior Door Module

General Motors, Delphi, and GE Plastics collaborated on the development of an interior door module, named the Super Plug, that consolidates up to 61 metal parts into a single molded unit. Currently, a sheet metal door panel skin slides over the "super plug" composite module. Design work is currently underway to create a "single, integrated panel marrying the interior module and its outer skin."[39] The "Super Plug", made of a polyester / polycarbonate blend with 30% glass fiber reinforcement, is 3.3 lb lighter, has better sound deadening qualities and is 5-10% lower cost than the incumbent metal interior door module. With the additional cost savings that will arise if design efforts are successful at integrating the outer skin into the plastic composite part, this application seems likely to penetrate into all vehicles following a Type 1 substitution curve.

7.1.4 Case Study Three: Instrument Panel System with Composite, Structural, Cross-Vehicle Beam

Ford and Cambridge Industries developed a SMC structural cross member beam which supports the IP and the steering post, is able to absorb the shock load from 2 deploying air bags, incorporates the functions of heating, air conditioning, and ventilation ducts and simplifies the routing of wiring harnesses. Developed for the 1995 Ford Ranger and Explorer, the cost advantages of the cross-vehicle beam are in parts consolidation: 16 steel and plastic IP parts, the air duct, and the steering column support are consolidated into two parts.[40] The performance advantages include a 30% NVH (Noise Vibration Harshness) improvement in the air duct, 2-3 ponds of weight reduction of the system, and comparable or better crash safety due to a more stable mounting surface for the air bags, knee bolsters, and crush cans. As the performance advantage is dependent on public perception, it is assumed that this system could penetrate into economy vehicles following a type 2 penetration curve.

7.1.5 Case Study Four: Ford Taurus RTM Rear Floorpan

A cost model comparison was performed between a steel Ford Taurus rear floorpan and a minimum thickness RTM rear floorpan. This comparison is not favorable to composites as a floorpan design that was created for composites would reduce costs by incorporating other functions into the floorpan to consolidate parts and to add stiffness through design instead of through additional material. As shown in Figure 7.1, under the optimistic cost model assumptions shown in appendix F, an RTM rear floorpan is cost competitive with steel only up to production volumes of approximately 25,000. For part-by-part substitution, the main advantage for an RTM floorpan is low tooling cost and the limiting factors are material cost, cycle time, preform cost, and labor. Advances in resin systems and preform processes which may significantly improve part-by-part substitution competitiveness are addressed in sections 1.2 and 1.3. Without such resin system or preform advances, RTM floorpans will not be utilized by anything but niche platforms.

7.2 PREFORM FABRICATION

7.2.1 Description

Glass fiber preforms, which typically are made of continuous glass fiber mat, chopped-strand mat, or chopped rovings, form the structural reinforcement for a RTM part. When reinforcing anything more complex than a simple flat part with continuous mat, the mat is thermoformed into the desired shape. Continuous glass fiber mat offers the greatest structural reinforcement, but is limited by the low degree of draw obtainable, the material cost, and relatively high scrap rates compared to plenum preforms or directed fiber preforms.

The simplest and most labor intensive way to form the glass fiber into the desired shape is through hand layup of the glass fibers. For mass production, glass fiber preform shaping methods can be classified as thermoforming, plenum preforming, or directed fiber spray. In the thermoforming process, a glass mat (with a small amount of thermoformable plastic acting as a binder) is pressed into the end-part shape in a mold at elevated temperature. Plenum preforming attracts chopped glass rovings which are dropped into a plenum chamber onto a steel wire screen shaped to the desired end-part by the rapid suction of air through the screen. A thermoplastic binder in aqueous solution is sprayed onto the fibers to hold them in shape and the binder is dried. The preform is removed from the screen and the process is repeated.[41]

Lastly, chopped fibers can be sprayed onto a screen (again, shaped as the desired end part) by a directed nozzle at the same time as thermoplastic binder is sprayed on. This process has traditionally involved manual spraying of the fibers and the binder through hand held nozzles. However, Michael Jander of Owens Corning has recently developed a mass production version of this preforming process, named a Programmable, Powdered, Preform Process (P4). The P4 process utilizes robotized spray guns that can spray either randomly oriented or directed glass rovings onto a screen along with a dry thermoplastic binder which eliminates preform drying time.

7.2.2 Case Study: Thermoformed vs. P4 Preforms on Rear Floorpan

The P4 process was developed to bring the RTM process one step closer to economical mass production by adding approximately $1 Million[42] in fixed costs per production line in order to substantially reduce variable costs. Variable costs are primarily reduced through cheaper material costs. The chopped rovings utilized are a cheaper reinforcement than continuous strand mat and, as little or no trimming is required, the scrap is greatly reduced to approximately 1% compared to 10% to 40% scrap rates for thermoformed mats of varying complexity and with cutouts.[43] In addition, variable costs are reduced through the reduction of labor costs both due to automation and due to a reduction in cycle time.

In this thesis, the P4 process was compared with the thermoforming process for a simple geometry rear floorpan application in order to determine the production volume range where the added fixed costs of the P4 process were compensated for by the reduced variable costs. As shown in Figure 7.2, the P4 process becomes competitive with thermoformed mat in this application at production volumes of approximately 25,000 parts produced per year. The usefulness of this advance in the economics of the mass production of preforms is limited by the high variable costs of the remainder of the RTM process. In the region where P4 lowers the overall cost of the RTM floorpan, steel rear floorpans are cheaper than RTM rear floorpans. For part-by-part substitution of structural components with simple geometries, steel is a still the dominant material in all but very small niche volumes.

P4 does appear to provide an achievable cost advantage for parts with higher complexity, especially those that involve large cutouts and thus high scrap rates, heavier parts, and parts with multiple preforms. Heavier parts have a higher percentage of material costs and, thus, the material cost advantage of P4 over thermoformed preforms is more significant. In addition, P4 is suitable at lower volumes for parts that have multiple preforms, as the P4 equipment investment, which is assumed to be dedicated to the part, is amortized over the number of parts produced multiplied by the number of preforms per part.

7.2.3 Impact of Preforming Advances

As demonstrated in the case study in section 7.2.2 and figure 7.1, the P4 preforming advances will have little or no impact on relatively lightweight part-by-part substitution with a single preform without advances that make the remainder of the RTM process more suitable for mass production. For more complex systems that have been designed to consolidate several parts, such as the CIV front-end modeled in section 6.1, the RTM process is already competitive at production volumes of over 50,000 parts per year. The CIV front end system utilizes two glass fiber preforms, making P4 suitable at volumes between 10,000 and 15,000 parts per year. P4 preforming advances raise the economical production volume the CIV front-end from 80,000 parts per year (assuming aggressive scenario cure time of 15 minutes) to slightly more than 100,000 parts per year, as shown in figure 7.3.

Figure 7.1: Cost Model Comparison of a Structural Rear Floorpan with No Parts Consolidation

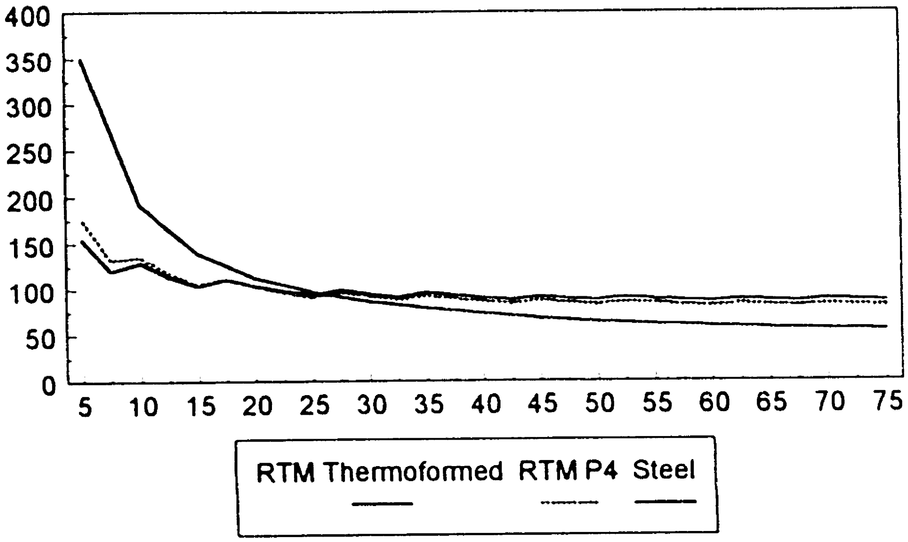
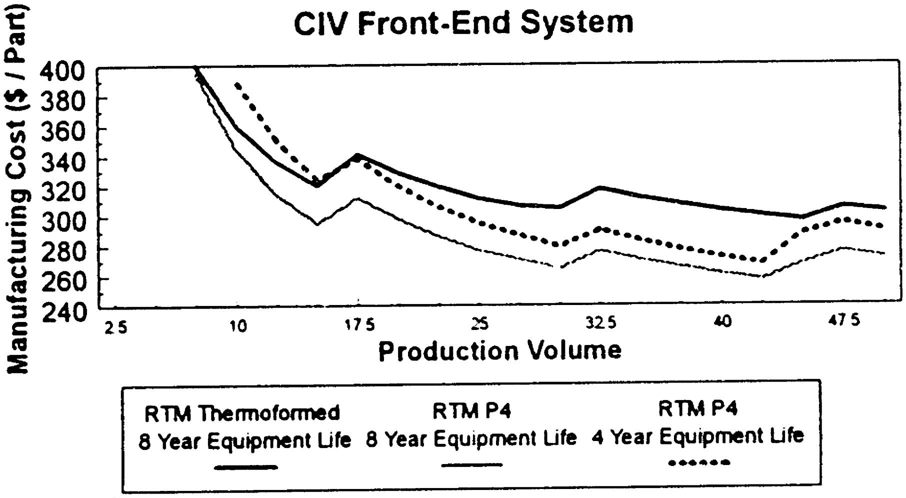


Figure 7.2: Cost Comparison of Thermoformed vs. P4 Preforms for the complex CIV front-end system



Cure time of 15 minutes
P4 preform is 100% random chopped fiber
Two glass fiber preforms per front-end

7.3 PROCESSING ADVANCES WITH DIFFERENT RESIN SYSTEMS

7.3.1 Description

The main cost advantage of the RTM process over steel for part-by-part substitution is the extremely low RTM press and mold costs per line. The main handicap to the RTM process at medium to high production volumes is the long cycle time which results in the need for multiple parallel streams of equipment and operating labor. For many applications, the cure time of the RTM part makes up between 50% and 75% of the total cycle time, making cure time reduction the dominant variable in the competitiveness of the RTM process at higher production volumes. The variables that control the time of cure for thermosetting resins are the activation energy and the rate coefficient of the material.[44] Vinyl esters, which are very chemically resistant resins when cured, have the disadvantage of a much slower curing rate than polyester resins. For either resin system, either cycle time or material costs need to be dramatically reduced in order for the RTM process to be competitive for part-by-part substitution at higher volumes.

A sister process to RTM, called Structural Reaction Injection Molding (S-RIM), is not investigated in this thesis, but its economic tradeoffs of lower cycle time along with higher equipment and material costs should be investigated at some future time. The S-RIM process allows for much reduced cure times due to the rapid reaction times of the polyisocyanate. However, equipment costs and material costs are significantly higher than in RTM. In addition, some cycle time advantages may be negated by ensuring adequate fill time for thorough wetting of the glass fiber preform before the curing can begin.

7.3.2 Sensitivity Analysis: CIV front-end

The CIV front-end system discussed in section 6.1 was modeled in steel and in RTM. A sensitivity analysis was performed in order to determine the cure time and material price levels at which the CIV front-end system would be cheaper than the steel Honda Odyssey front-end system at production volumes of 100,000 parts per year. Economical production at volumes of 100,000 parts per year could be achieved if molding cycle time (including placing preform in mold, filling mold, and cure to 85% conversion) was reduced to 15 minutes, P4 was incorporated, and resin prices did not increase. This reduction in cure time, without a counterbalancing increase in equipment or material costs, would represent a major breakthrough in the RTM process. It is, however, within the goals of the CIV project and viewed as eventually achievable.

7.3.3 Impact of Resin Advances

Given the assumptions made in the case study in section 7.3.2, RTM would be a suitable candidate for substitution in semi-structural and structural parts whenever significant parts consolidation is possible. For production volumes less than 100,000 vehicles, RTM parts would substitute into entire front-end systems and floorpans across all vehicles. If these resin and preform advances are in conjunction with the design advances in section 7.1, all type 2 and type 7 structural composite penetrations would convert to type 1.

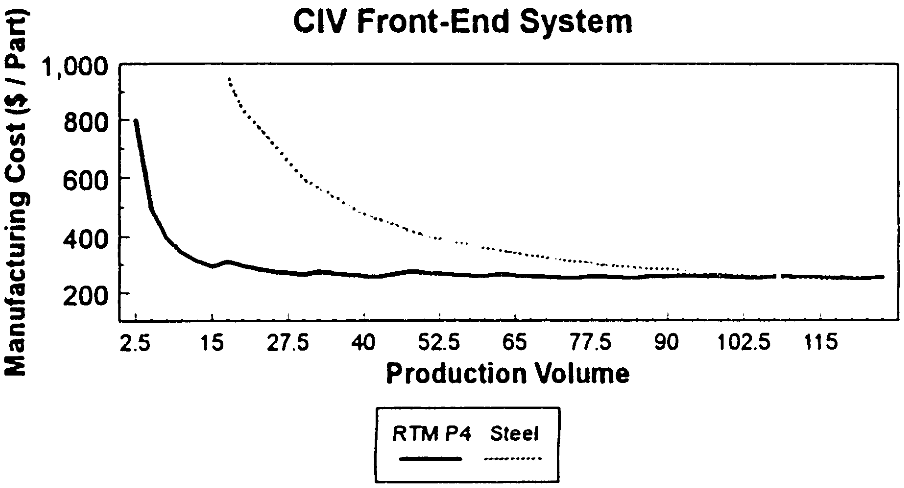
7.4 AGGRESSIVE SCENARIO OF PROCESS, DESIGN, AND MANUFACTURING ADVANCES

In the aggressive scenario of process, design, and manufacturing advances, it is assumed that a cure time of 15 minutes is achievable for the CIV front end system modeled in chapter 6, and resin prices remain constant. It is also assumed that the P4 process is used in the manufacture of the two glass fiber preforms in the front end. Thus, the CIV front end system prototype is economical at production volumes up to 100,000 parts per year and, as the system is also lightweight, it is assumed to penetrate into all vehicles following a Type 1 penetration curve, resulting in a net increase of 15 pounds per vehicle. Another RTM structural part that involves large amounts of parts consolidation, the integrated floorpan with rear seatbacks is assumed to be similarly economical up to production volumes of 100,000. This integrated floorpan is assumed to penetrate into all vehicles following a type 1 penetration curve, resulting in a net increase of 23 pounds per vehicle. In addition, all design advances described in section 7.1 are achieved. The impacts of these design advances are described in the moderate scenario in section 7.5. Thus, the total impact of design, process, and manufacturing advances is a net increase of 65 pounds per vehicle by 2015.

7.5 MODERATE SCENARIO OF PROCESS, DESIGN, AND MANUFACTURING ADVANCES

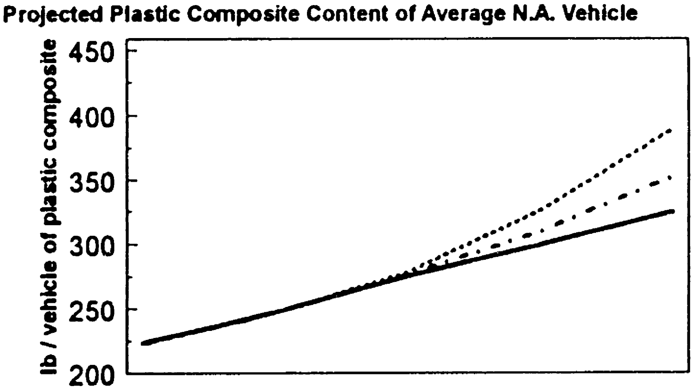
In the moderate scenario, it is assumed that no breakthroughs occur in substantially reducing cure time with a low cost resin. We also assume that no RTM applications are economical at high enough production volumes for the P4 preforming process to have any impact. Therefore the only increase in plastic composite consumption is due to design advances outlined in section 7.1. The SMC integrated front-end system penetrates into all vehicles following a Type 1 penetration curve, resulting in a net increase of 11.2 pounds per vehicle by 2015. The injection molded thermoplastic composite door assembly penetrates into all vehicles following a Type 3 penetration curve, resulting in a net increase of 1.35 pounds per vehicle by 2015. The RTM rear floorpan penetrates into vehicles with production volume less than 20,000 following type 1 penetration curve, resulting in a net increase of only .3 pounds per vehicle. Lastly, the instrument panel cross vehicle beam penetrates into all vehicles following a Type 1 penetration curve, resulting in a net increase of 14.6 pounds per vehicle. Hence the total impact of the of the design advances is a net increase of 27.4 pounds per vehicle.

Figure 7.3: Aggressive Scenario for Design, Resin and Preforming Advances



Cure time of 15 minutes
P4 preform is 100% random chopped fiber
Two glass fiber preforms per front-end

Figure 7.4: N.A. Scenarios on Design and Process Advances



Year	1995	2000	2005	2010	2015
Baseline —	223	247	275	299	324
Aggressive ----	223	247	278	325	389
Moderate -·	223	247	276	309	352

Chapter 8: Summary and Recommendations

8.1 SUMMARY OF BASE CASE AND SCENARIO RESULTS

The baseline projection of plastic composite content in North America results in 324 pounds per average vehicle by 2015. As shown in figure 8.1, the scenarios range from a low of 237 pounds per vehicle under aggressive recycling assumptions to a high of 458 pounds per vehicle under aggressive CAFE assumptions. Given vehicle growth estimates outlined in Appendix A, the resultant plastic composite contents translate into vastly different volume projections for plastic composite suppliers to the automotive industry: the basecase projected volume of 6.5 billion pounds per year of plastic composite required by the North American automotive market could alter to a low of 4.7 billion pounds in the recycling scenario or a high of 9.1 billion pounds in the fuel economy scenario. Corresponding regional ranges of scenario impacts are illustrated in figures 8.2 and 8.3. The extremes of these projections could mean either the decision to construct several additional glass fiber plants and three or four extra resin plants over the basecase projection or substantial oversupply in the automotive market and perhaps the entire composite industry. Exploring the implications of these scenarios over a twenty year horizon are important to the strategic planning process, as the lead times for the planning and construction of new plants can be five to ten years.

Scenario analysis can be used to estimate expected projections of polymer consumption. The baseline projection, which is the projection without any discontinuities, is not always the best forecast of the future. Hence, the likelihood baseline assumptions being correct is assigned a probability. The expected result is calculated by factoring in the probabilities of alternate scenarios occurring.

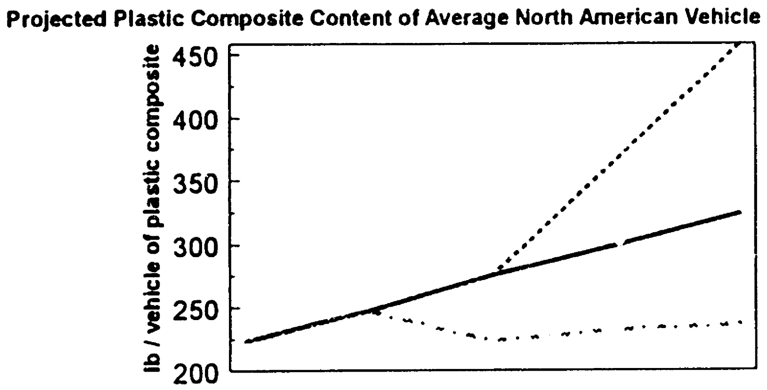
8.2 LIKELIHOOD OF OCCURRENCE OF VARIOUS SCENARIOS

For the two external regulatory scenarios, the likelihood of baseline, moderate, or aggressive scenarios occurring will depend mainly on regulatory actions and industry pressures. The scenarios are based on current regional legislation and industry proposals. A 50% probability is assigned to the baseline projection and 25% probabilities to both the moderate and the aggressive scenarios. These probabilities can be refined as future events unfold.

For the two technological scenarios, internal to the plastic composite industry, probabilities can be assigned based on the expectation that a particular technological advance will be achieved. In the revolutionary vehicle scenario, achieving a cure time of 15 minutes for the CIV frond-end system is within the goals of the CIV program. The probability of achieving this reduced cure time without significant increase in resin prices and equipment costs is estimated at 50%. Even with these reduced cure times, cost advantages are likely to be limited to systems exhibiting parts consolidation as most assembly costs are eliminated. It is estimated that there is a 40% probability of the moderate scenario occurring, and a 10% probability of the aggressive scenario occurring.

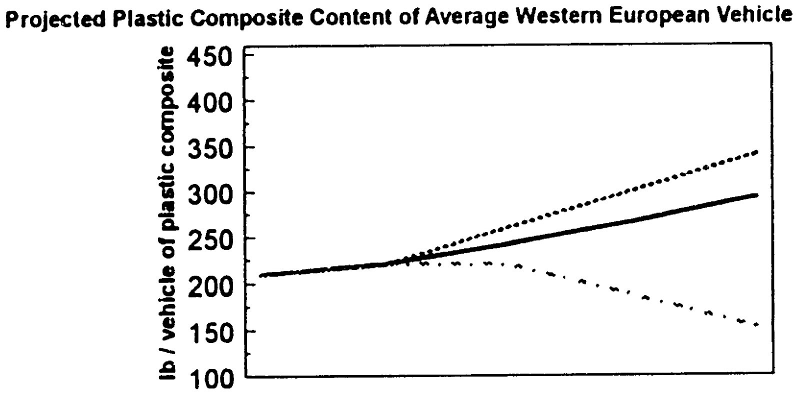
Some design and manufacturing inertia is assumed in assigning probabilities to the incremental design, manufacturing, and process advances scenarios. A 40% probability is assigned to the baseline projection in which none of the design advances examples are transferable across platforms, no increased cure times are achievable and adoption of P4 technology is unsuccessful. The moderate scenario of design advances alone occurring is assigned a probability of 35%. And the scenario where design advances are transferable across platforms, significantly reduced cure times are achievable, and P4 preforming technology is successfully adopted is assigned a probability of 25%. Figure 8.4 illustrates the range of expected values of global automotive plastic composite consumption given the above probabilities.

Figure 8.1: Range of Aggressive Scenario Impacts in N. America



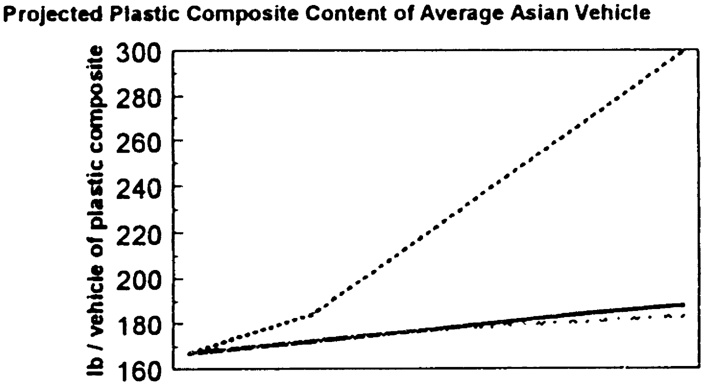
Year	1995	2000	2005	2010	2015
Baseline —	223	247	275	299	324
Fuel Economy ····	223	247	275	366	458
Recycling - ·	223	247	223	232	236

Figure 8.2: Range of Aggressive Scenario Impacts in W. Europe



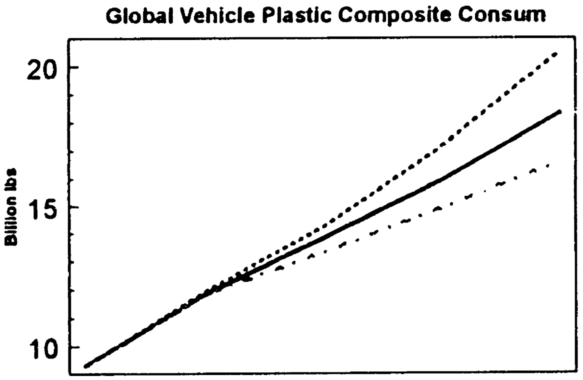
Year	1995	2000	2005	2010	2015
Baseline —	209	220	242	266	293
Fuel Economy ····	209	220	260	300	340
Recycling - ·	209	220	220	187	153

Figure 8.3: Range of Aggressive Scenario Impacts in Asia



Year	1995	2000	2005	2010	2015
Baseline —	167	172	177	183	188
Fuel Economy ····	167	184	222	260	299
Recycling -·	167	172	177	180	183

Figure 8.4: Range of Expected Value of Scenario Impacts Globally



Year	1995	2000	2005	2010	2015
Baseline —	9.3	11.8	13.8	15.9	18.3
Expected Value Fuel Economy ··	9.3	11.9	14.2	17.1	20.5
Expected Value Recycling -	9.3	11.8	13.3	14.9	16.6

8.3 RECOMMENDATIONS TO PLASTIC COMPOSITE SUPPLIERS

The scenario analysis constructed in this thesis indicates that composite demand in the automotive market would be more effected in the medium-term future by regulatory discontinuities than by technical discontinuities. This is because a dramatic lowering of costs is required in order to favor cost driven substitutions in the higher production volume platforms representing the bulk of the automotive market. Under an environmental legislative discontinuity, production cost is no longer the primary driver of substitution, and composites face elimination from or greater access to the automotive market based on features such as recyclability and weight reduction. A strong industry voice in automotive legislation circles, comparable to the voice of the steel or aluminum industries, could have more influence on future plastic composite demand than technological advances.

8.4 SUMMARY ON METHODOLOGY

Dynamically projecting material demand based on a part-by-part analysis of potential future substitution lessens the arbitrariness of a long-term projection. The use of both performance and cost specific logistics curves to model part and system substitution in a market niche where performance and cost attributes stay relatively constant enables the analysis to be updated and checked against actual substitution. For emerging system designs with unknown cost attributes, technical cost models can assess the system's competitiveness relative to the incumbent material. The complexity of a useful management forecasting tool is usually limited by the lack of time managers have to devote to building the forecast. This methodology does not appear to be overly time consuming to update and appears more robust for a long term forecast than a macroeconomic tool.

8.5 RECOMMENDATIONS FOR FUTURE WORK

Future work recommendations are mainly directed at refining assumptions that go into the scenario and determining the likelihood of a given scenario's occurrence. In order to refine the assumptions for the external scenarios, further regional analysis of legislation, and a more detailed comparison of alternative recycling economics would be helpful. For the technological scenarios, Paul Kang's work is ongoing on the cost comparison of the CIV vs. the steel Honda Odyssey. An interesting extension of this work would be to compare the economics of the S-RIM process to that of RTM for the CIV. Other advancing plastic technologies, such as the thermoforming of oriented plastics, could be investigated. For all scenarios, assumptions regarding potential cost and lightweighting advances of steel and aluminum could be incorporated.

Additionally, the need for a catalyst to adoption, outside of favorable cost and performance attributes, could be studied. An example of a catalyst to adoption is the requirement that the 1996 Ford Taurus / Sable have a cab forward design. The cab forward design requirement meant that the existing steel front-end system had to fit into a much smaller space with all of its components (see 7.1.2). The design team subsequently examined many potential materials and designs to fit the requirements and decided on two SMC parts which were cheaper and lighter than the steel system. Even with the favorable cost and performance attributes, would the SMC parts have substituted for the steel without the added push of the cab forward design requirement? Answering this question for some historical examples of automotive part substitution could help refine the logistics curve analysis employed in this thesis.

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Appendix A: Vehicle Growth Estimates

Vehicle Growth Estimates

Total Projected Car and Light Truck Production by Region (in millions)

	NAFTA	W. Europe	E. Europe	Asia	L. America	Other	Total
1990	11.99	15.01	2.20	14.93	0.95	0.48	45.55
1995	14.94	13.88	2.25	14.20	1.87	0.68	47.81
2000	17.20	15.83	3.64	17.20	2.89	0.72	57.47
2005	18.06	16.46	4.00	19.78	3.12	0.74	62.16
2010	18.96	17.12	4.40	22.75	3.37	0.77	67.37
2015	19.91	17.80	4.84	26.16	3.64	0.81	73.16
Growth Rate over 5 Years	5%	4%	10%	15%	8%	4%	

Historical Production of All Vehicles by Region (in millions)

	NAFTA	W. Europe	Asia	ROW	Total
1985	13.83	12.10	13.80	4.57	44.30
1986	13.51	13.19	13.89	4.76	45.35
1987	13.05	13.95	14.39	4.90	46.29
1988	13.69	14.79	15.15	5.51	49.14
1989	13.48	15.53	15.51	5.59	50.11
1990	12.54	15.07	15.97	6.37	49.95
1991	11.69	14.47	16.11	6.37	48.64
1992	12.74	14.49	15.85	5.97	49.05
1993	14.22	12.11	15.06	6.42	47.81
1994	15.56	13.28	14.97	6.87	50.68
1995	15.36	13.92	15.16	7.11	51.55
Average Annual Growth Rate	1.3%	1.7%	1.0%	4.7%	1.6%

Historical Total Passenger Car Production by Region (in millions)

	1980	1985	1990	1995
NAFTA	7.52	9.51	7.49	8.36
W. Europe	11.11	12.03	13.67	12.62
E. Europe	0.86	2.24	1.77	2.04
Asia	7.14	8.01	11.43	10.51
L. America	1.12	0.83	0.75	1.57
Other	0.32	0.38	0.36	0.56
Total	28.07	33.00	35.47	35.67

Sources for Historical Numbers include: World Industry Forecast Report, DRI, and Ward's Automotive Handbook

Appendix B: Inputs to RTM and P4 Models for CIV Analysis

MATERIALS SYSTEMS LABORATORY
RESIN TRANSFER MOLDING COST MODEL
January 1997

MANUFACTURING SPECIFICATIONS

Annual Production Volume	20,000 /yr	NUM
Product Lifetime	4 yrs.	PLIFE
Working Days per Year	250 days/yr.	DAYS
Working Hours per Day	20 hrs./day	HOURS
Average Downtime	15.00%	DOWN

MATERIAL SPECIFICATIONS

Material Components

	Menu Selection	Weight %	
Resin	7	40.50%	RES, RESWT
Filler	1	9.50%	FILL, FILLWT
Reinforcement	5	42.00%	REIN, REINWT
Catalyst	1	0.50%	CAT, CATWT
Foam Core	2	7.50%	FOAM, FOAMWT
		100.00%	

Selected Material Characteristics (from menu)

Resin:

Component Name	Dow Derakane	
Density	1000 kg/m^3	RDEN
Viscosity	0.425 Pa*sec	RVIS
Price	$3.75 /kg	RESCOST

Filler:

Component Name	Calcium Carbonate (fine)	
Density	2700 kg/m^3	FILLDEN
Price	$0.13 /kg	FILLCOST

Reinforcement:

Component Name	OCF CSM M8605	
Density	550 kg/m^3	RFDEN
Fiber Diameter	0.000054 m	RFDIA
Price	$2.89 /kg	RFCOST

Foam Core:

Component Name	Mobay Bayflex 110-80 IMR	
Isocyanate Price	$2.54 /kg	ISOCOST
Polyol Price	$2.54 /kg	POLYCOST
Density	96.15 kg/m^3	FCDEN

Catalyst:

Component Name	Akzo Cadox M50	
Density	1200 kg/m^3	CDEN
Price	$3.24 /kg	CATCOST

Kinetic Data (Resin):

Polymer System	VINYL ESTER	POLYMER1
Rate Coefficient	8.00E+07 /sec	RATE1
Activation Energy	7.66E+04 J/mol	ACTIV1

Kinetic Data (Foam Core):

Polymer System	POLYURETHANE	POLYMER2
Rate Coefficient	1.27E+05 /sec	RATE2
Activation Energy	3.89E+04 J/mol	ACTIV2

MOLDED PART

Maximum Part Length	1.4 m	PLEN
Maximum Part Width	0.575 m	PWIDTH

Average Part Thickness	1.00E-01	m	PTHK
Surface Area	0.4446	m^2	PSURF
Perimeter	4.056	m	PPER
Total Volume	4.45E-02	m^3	PVOL
Total Weight	22	kg	PWGT
No. of Inserts	0		NUMINS
Insert Weight	0	kg	IWGT
Insert Volume	0	m^3	IVOL
Average Insert Price	$1.00	/insert	INSCOST

FOAM CORE

How many foam cores needed? (Assumes all are unique)	2	(1,2,3 foam cores)	FCNUM

Foam Core 1

Maximum Length	0.8	m	FLEN1
Maximum Width	0.2655	m	FWIDTH1
Average Thickness	0.0909	m	FTHK1
Surface Area	0.1128	m^2	FSURF1
Volume	1.03E-02	m^3	FVOL1
Weight	1.0189	kg	FWGT1

Foam Core 2

Maximum Length	0.891	m	FLEN2
Maximum Width	0.1364	m	FWIDTH2
Average Thickness	0.0593	m	FTHK2
Surface Area	0.1071	m^2	FSURF2
Volume	6.35E-03	m^3	FVOL2
Weight	0.6311	kg	FWGT2

Foam Core 3

Maximum Length	0	m	FLEN3
Maximum Width	0	m	FWIDTH3
Average Thickness	0	m	FTHK3
Surface Area	0	m^2	FSURF3
Volume	0.00E+00	m^3	FVOL3
Weight	0	kg	FWGT3
No. of Inserts	0		NUMINS_FC
Insert Volume	0	m^3	IVOL_FC
Insert Weight	0	kg	IWGT_FC
Average Insert Price	$1.00	/insert	INSCOST_FC
Iso/Poly Weight Ratio	1		RATIO

PREFORM

How many preforms needed? (Assumes all are unique)	2	(1 or 2 preforms)	PFNUM

Preform 1

Maximum Length	1.400	m	PFLEN1
Maximum Width	1.076	m	PFWIDTH1
Average Ply Thickness	0.000843	m	PFTHK1
Surface Area (w/o cutout)	1.5064	m^2	PFSURF1
Cutout Area	0	m^2	CAREA1
Perimeter	4.056	m	PFPER1
Cutout Perimeter	0	m	CPER1
Number of Plies	3		NUMPLY1
Weight	4.39	kg	PFWGT1

Preform 2

Maximum Length	1.400	m	PFLEN2
Maximum Width	1.189	m	PFWIDTH2
Average Ply Thickness	0.000843	m	PFTHK2
Surface Area (w/o cutout)	1.665	m^2	PFSURF2
Cutout Area	0	m^2	CAREA2
Perimeter	4.056	m	PFPER2
Cutout Perimeter	0	m	CPER2
Number of Plies	3		NUMPLY2
Weight	4.85	kg	PFWGT2
Volume Fraction of Reinforcement	0.1804		VOLFRAC

Permeability	2.74E-09	m^2	RFPERM

EXOGENOUS COST FACTORS

Direct Wages	$20.00	/hr	WAGE
Capital Recovery Rate	12%		CRR
Capital Recovery Period	10	yrs	CRP
Electricity Price	$0.10	/KWh	ELEC
Auxiliary Equipment Cost	15%		AUX
Installation Cost	20%		INSTALL
Overhead Burden	35%		OVHD
Maintenance Cost	10%		MAINT
Price of Building Space	$807.29	/m^2	BLDG
Building Recovery Life	20	yrs	BLIFE

CONSTANTS, CONVERSION FACTORS

Universal Gas Constant	8.314	J/mol*K	GASK
Pascals to tons/m^2	1.11E-04	Pa/(ton/m^2)	PASC_TON
N to tons	2.22E-03	ton/N	NEWT_TON

P4 PREFORMING PARAMETERS

Preform Part Surface (m2)	1.5064		2334.92	SQ IN
Preform Mean Thickness (mm)	2.5		0.098	IN
Binder Price (dry)	$2.27	$/lb		PFOURBIND_
Glass Roving Price	$0.82	$/lb		PFOURROVE
Veil Price	$0.82	$/lb		
Continuous Fibre Price	$0.82	$/lb		
Glass/Resin Scrap Rate	3%			PFOURSCRP
P4 Preform Production	100	000 / yr		
Number of Preforms per part	2			
Preforming Machine (incl spray gun)	1,000,000	/sta		PFOUR_INVE
Forming Screens	64,000	$		PFOURSCRE
Number of Laborers	0	/sta		PFOURLAB
Preformer Energy Requirement	33.03	kW		PFOURENGY
Plenum Pref. Floorspace Req.	3875.00	sq ft		PFOURSPAC

Veil Planer Density (g/m^2)	40		0.13	OZ / SQFT
Chopped random fibers Planer Density (g/m^2)	1350		4.43	OZ / SQFT
Chopped oriented fibers Planer Density (g/m^2)	0		0.00	OZ / SQFT
Continous fibers Planer Density (g/m^2)	0		0.00	OZ / SQFT
Binder Planer Density (g/m^2)	90		0.30	OZ / SQFT
Filler Planer Density (g/m^2)	0		0.00	OZ / SQFT

Wt% Veil	2.70%			
Wt% Chopped Random Fibres	91.22%			
Wt% Chopped oriented Fibres	0.00%			
Wt% Continuous Fibres	0.00%			
Wt% Binder (dry)	6.08%	wt %		PFOURBIND
Wt% Filler	0.00%			

Glass Delivery System

Nominal Throughput of Veil (g/min)	450	15.89	oz / minute
Nominal Throughput of Chopped Random Fibre	6000	211.80	oz / minute
Nominal Throughput of Chopped Oriented Fibre	1500	52.95	oz / minute
Nominal Throughput of Continuous Fibre	1000	35.30	oz / minute
Veil Coefficient of Utilization	80%		
Chopped Random Fibre Coefficient of Utilization	60%		
Chopped Oriented Fibre Coefficient of Utilization	60%		
Continuous Fibre Coefficient of Utilization	20%		

Cycle Time Inputs

Press Cycle (Heat + Cool + Open)	40	seconds
Demolding	10	seconds
Transfer	10	seconds

Assigning Tasks to Stations (four stations)

Station for Veil Placement	1
Station for Chopped Random Fibre Placement	1
Station for Chopped Oriented Fibre Placement	1
Station for Continous Fibre Placement	1

Station for Press Cycle	2
Station for Demolding	3

GENERAL COMPONENT SPECIFICATION

Surface Area	2,335	sq in	SAREA
Projected Area	0	sq in	PAREA
Maximum Part Length	55.1	in	LEN
Maximum Part Width	46.8	in	WID
Average Molded Skin Thickness		in (see menu #	THICK
Total Part Weight (excl coatings)	48.4	lbs	WGT
Annual Production Volume	50	000/yr	NUM
Product Lifetime	4	years	PLIFE
Dedicated Capital Equipment (Y/N)	1	(1=yes,0=no)	DED
total rtm process scrap rate	5%		

MATERIAL SELECTION & WEIGHT PRECENT

	menu #	wgt %	
Resin		40.5%	RES,FR
Catalyst, Hardener, or Initiator		0.5%	CAT,CR
Filler or Chopped Glass (0=none)		0.0%	FIL,FF
Fiber Mat Reinforcements		0.0%	FB
Plenum Preform		0.0%	FP
P4 Preform		51.5%	PFOUR
Foam Core		7.5%	FC
		100.0%	

FIBER MAT SELECTION & PLY COUNT

	menu #	% of Reinforcement	
First Fiber Mat Material (0=none)	14	100%	FIB1,PLY1
Second Fiber Mat Material (0=none)	0	0%	FIB2,PLY2
Third Fiber Mat Material (0=none)	0	0%	FIB3,PLY3
		100%	

Number of Veil Plies (0, 1, or 2)	0		VEIL
Veil Area Density	0.13	oz/sq ft	VL_DENS
Veil Price	$0.82	/lb	VL_PRICE

EXOGENOUS COST FACTORS

Direct Wages (w/ benefits)	20	/hr	WAGE
Working Days per Year	240		DAYS
Working Hours per Day	24		HRS
Labor & Equipment Productivity	85.0%	of tot time	PRD
Capital Recovery Rate	12%		CRR
Working Capital Period	2	mo	WCP
Equipment Recovery Period	8	yrs	CRP
Electricity Price	$0.100	/kWh	ELEC

Auxiliary Equipment Cost	30.0%	of fc	AUX
Installation Cost	20.0%	of fc	INST
Overhead Burden	35.0%	of fc	OVHD
Maintenance cost	5.0%	of fc	MNT
Building Space Price	$85.00	/sq ft	RENT
Building Recovery Life	25	yrs	BLDL

<END>