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**TECHNO-ECONOMIC REQUIREMENTS  
FOR AUTOMOTIVE COMPOSITES**

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New technology generally serves two main goals of the automotive industry: one is to enable vehicles to comply with various governmental regulations and the other is to provide a competitive edge in the market. The latter goal can either be served through improved manufacturing and design capabilities, such as computer aided design and computer aided manufacturing, or through improved product performance, such as anti-lock braking (ABS).

Although safety features are sometimes customer driven, such as the increasing use of airbags and ABS, most are determined by regulations as outlined by the Federal Motor Vehicle Safety Standards (FMVSS). Other standards, set by the Environmental Protection Agency, determine acceptable levels of emissions and fuel consumption. State governments, such as in California, are also setting precedent standards, such as requiring manufacturers to offer zero-emission vehicles as a certain fraction of their sales in the state.

**The Role of New Technology in the Automotive Industry**

- **A capability to satisfy future regulatory constraints on fuel consumption, safety, and emissions**

Customer driven

Government regulations

- **Strengthen the ability for world class competition**

The drive to apply new materials in the automobile stems from the need to reduce weight and improve fuel efficiency. While fuel efficiency is partly driven by the market, the main “customer” is the EPA and its CAFE ratings. Primary weight savings are achieved through direct replacement of the current material, steel for example, with a lower density material. Primary savings create opportunities for secondary reductions through resizing other components of the vehicle which are sensitive to weight, such as the powertrain and suspension. Lighter body structure, through primary savings, leads to smaller engine and chassis structure. Secondary savings, however, are usually not realized in practice until the entire vehicle is redesigned--usually a product generation after the primary savings are made.

Light weight materials create opportunities to add new customer driven features while maintaining the weight class of the vehicle. Additional devices for compliance with safety, emissions, and other regulations require weight to be eliminated to maintain fuel economy ratings. Direct replacement of structures with lightweight materials offers one of the most effective means to reduce vehicle weight without having to invest in redesigning the structure and powertrain. However, if the investment in design and engineering is available, lightweight materials can offer significant performance advantages in dynamic applications, such as connecting rods and pistons, where lower inertial loads lead to overall powertrain downsizing. Other benefits include better noise, vibration, and harshness (NVH) due to the better damping capabilities of some composite materials.

### **New Lightweight Materials: A Critical Element of Future Automotive Technology**

- **Drastically improved fuel economy**
- **Provide substantial secondary weight savings through total systems downsizing**
- **Higher “payload” weight fraction**
  - Customer features
  - Regulatory compliance features
- **Improved “NVH” and Quality**
  - Better damping
  - Low dynamic masses

The automotive industry remains one of the largest users of steel. Most automotive basic manufacturing technology centers around the forming and assembly of steel structures. However the scope of materials used in the automobile can be divided roughly into sheet, bar, and bulk applications. Sheet applications are divided into sheet metal (steel and aluminum) and plastics. The majority of automotive structure today is composed of sheet steel. There are limited applications where aluminum is being processed on the same manufacturing infrastructure as steel. Plastic sheet materials are divided into thermoplastics and thermosets which can each be divided into composites and NEAT materials. SMC is a thermoset composite which is becoming increasingly common in non-structural applications. Thermoplastic composites, such as glass filled polypropylene (e.g. Azdel or Taffen) are used in applications where impact resistance is important such as bumper beams and load floors.

Bar applications cover those parts which serve as heavily loaded structure such as moving engine components, chassis parts, brake rotors, etc. Most of these applications are suited for metals except in some cases where structural fiber reinforced plastics are acceptable. Currently many applications using steel are being replaced with either forged or cast aluminum. Intake manifolds are an example where iron was replaced by aluminum which is now starting to be replaced by engineering plastics.

The bulk applications include housings and interior systems such as the instrument panel. These types of components can easily take advantage of the low manufacturing cost and lightweight of die cast aluminum, magnesium (in the future), and injection molded thermoplastics

## **Types of Automotive Materials**

- **Sheet Applications**

Sheet Metal: Aluminum and Steel

Plastics: SMC, GTP (Azdel), TPs

- **Bar Applications**

Castings: Aluminum, Iron, Magnesium, and Zinc

Extrusions: Aluminum

Forgings: Aluminum and Steel

Plastics: FRP

- **Bulk Applications**

Castings: Aluminum, Iron, Magnesium, and Zinc

Moldings: FRP and TP

Composite materials are being used by the automotive industry at an increasing rate mainly in non-structural body closures such as hoods and decklids. They offer reduced weight and, in some cases, lower investment cost. However, continued acceptance of these materials has slowed as the applications have become more integral to the body structure and critical to crash energy management. There are many barriers to using a new material which include both design limitations as well as manufacturing incompatibility. Design limitations are centered on the difficulties using a single material system for large scale parts integration. This prevents cost-effective materials substitution since the vehicle design has been optimized with steel. The vehicle needs to be re-designed and optimized with the new material to achieve the same cost-effectiveness as with steel.

The limitations to designing reliable crash energy management structures are closely coupled to the difficulties associated with producing composites with predictable properties. The automotive industry is largely devoted to metal forming and assembly. These basic manufacturing processes are very different from the processes used to produce most fiber reinforced plastics. Compression molded SMC and BMC are somewhat similar to automotive mass production, yet they do not produce materials which are capable of efficient use in highly loaded structural applications. Aerospace composite materials, on the other hand, have enough control placed on the alignment and wet-out of the fibers to achieve high structural reliability. Aerospace manufacturing control is far too costly for application in mass production. Thus the challenge is to develop processes with optimal control and cost for mass production of structural composites.

## **Automotive Composite Applications**

- **Potential candidates for lightweight body applications**

- **Initial acceptance barriers:**

Design	}	Effect Product Cost
Manufacturing		

- **Exterior Applications**

Structural

Non-structural

- **Interior Applications**

The body-in-white (BIW) has the greatest potential for application of fiber reinforced plastics. However, the BIW is highly integrated and requires extensive re-design in order to substitute new materials for steel. Many chassis components, on the other hand, are bolted on to the frame or underbody and offer simpler materials substitution opportunities. For example, crossmembers, which are bolted on to the frame rails, are low risk candidates for composite materials. Little or no change to the assembly line is required and the carry-over steel component can be used as a back up if the composite development program fails. When part of the BIW is replaced with a different material, so many changes in the design and manufacturing process are required that the expense and risk may outweigh the benefits. The best strategy for offsetting the risk and cost against the benefits of new technology is to apply it where the current technology remains an acceptable alternative. This way, if the new technology is unsuccessful, the entire program is not jeopardized.

## **The Role for Composite Materials in Automotive Applications**

- **Structural Applications**

  - Body-in-White, e.g. Floor-pan

  - Chassis and Powertrain, e.g. Crossmember and Drive Shaft

  - Engine, e.g. Block

- **Non-Structural Applications**

  - Exterior Body Panels, e.g. Hood

  - Interior, e.g. Load Floor

  - Bumper Fascia

Composite materials have very high specific properties which make them very attractive alternatives to ferrous metals in weight sensitive structural applications. These weight efficiencies are attainable at relatively low cost since most polymer-based composites are priced the same or lower than lightweight metals. In structural applications conventionally held by stamped and welded sheet steel, polymer composites offer lower investment cost since they can be processed in fewer steps requiring expensive tooling. Composite molding processes are capable of producing large structures which integrate many of the equivalent components in the steel application. Combined with fewer operations, polymer composites have significant low investment advantages not common in sheet metal forming.

There are other physical performance merits composites possess such as damage tolerance and energy absorption. However, the difficulty of achieving reliable performance in crash is complicated by process and design limitations. It is currently very difficult to produce low cost composite parts with high structural reliability in crash-worthy applications.

### **Composite Materials: Advantages**

- **High specific mechanical properties**
- **Relatively low materials costs (relative to Aluminum and Magnesium)**
- **Potential for low investment**
- **High capability for developing integrated structures**
- **Improved damage tolerance and energy absorption**

The disadvantages of automotive composites arise mainly in the comparison with sheet steel. Much of the automotive industries' basic manufacturing capacity, world-wide, is in forming and assembling steel sheet. Composites have significantly higher materials cost relative to steel even when adjusted for the lower density. The cycle times of most molding operations are significantly longer than steel stamping operations even though the latter requires several steps. One of the most efficient means to low cost composites is to reduce part count from the equivalent steel assembly. Consolidation with composites reduces both recurring and nonrecurring (tooling) costs.

Since steel is the traditional material used in automotive structure, there remains significant resistance to using new materials, such as composites. This resistance is primarily rooted in limitations to understanding how to effectively design with composites. Further limitations are due to the existing manufacturing capability. Since automotive companies are capitalized to process steel they look to suppliers to produce non-ferrous components. It is likely that capital could be replaced by machinery to process new materials. However, the rate and timing of this process is still undetermined.

### **Composite Materials: Disadvantages**

- **High materials cost (relative to Steel)**
- **High recurring manufacturing cost (relative to metal processes)**
- **Limited existing design tools and experience**
- **Limited compatibility with existing structures and manufacturing operations**

The economics of competing materials systems must be assessed on two levels: the material and the processing cost. For sheet type systems such as sheet metal or plastic films, aluminum is one of the highest priced and steel is the lowest priced. Plastic sheet materials fall into a spectrum of prices depending on the performance criteria. Thermoplastics tend to be priced higher than thermoset materials. For profile sections (moldings, castings, and extrusions), NEAT and reinforced polymers tend to cost more than metal castings and extrusions.

Processing costs can be broken up into fixed and variable costs which are also referred to as nonrecurring and recurring costs. Tooling and direct equipment costs are driven by the process and tend to be lower for plastics and composites than metals processing, especially for sheet materials. This relationship is due to the fewer operations to make plastic parts when compared with the steps or conditions necessary to process metals. Labor cost is driven by the cycle times of the individual steps in the production process. Plastics and composites usually have long cycle times, although few steps, when compared to metals processing. When comparing plastics and composites to metals, the high variable and low fixed costs of the former are combined to give low production volume advantages. At higher production volumes, however, metals usually yield lower unit costs.

## Material Substitution Economics: Overview

- **Material Cost:**

Sheet: Al>TP>FRP>Fe

Profiles: FRP<sub>2</sub>>Al>Fe

- **Processing Cost**

Tooling: Al>Fe>FRP

Equipment: Al,Fe>>FRP

Labor: FRP>Al,Fe

Recurring: FRP>Al,Fe



To further illustrate the role of lightweight materials in the automotive industry, consider their role in the aerospace market. The customer of aerospace systems demands low weight since it directly impacts the economics of the mission. The military needs to reduce weight in air vehicles to increase the payload, while the commercial airline industry wants to minimize fuel costs and maximize passenger capacity. At current fuel prices, the automobile buyer is usually not basing purchasing decisions on the fuel economy of the vehicle. It is the EPA who demands a certain fuel efficiency through CAFE standards. The automotive producers must determine the optimum weight reduction premiums based on product mix, profit objectives, and vehicle weight class constraints.

Like the automotive industry, the aerospace industry has focused its manufacturing capability around a single class of materials. For the most part, aircraft are constructed from aluminum bar, plate, and sheet. Military aircraft often contain a considerable amount of titanium. Unlike automotive applications however, aerospace production volume tends to be very low. The service reliability of aircraft has to be very high since the performance objectives of the structure are very high. Thus aerospace production methods rely heavily on using very high quality and cost materials with extensive testing and inspection of finished products. The low production rate with extensive inspection steps, of normal manual operations, enables composite materials to integrate into aerospace structure without creating havoc in the process. Automotive production requires reliability to be maintained through process control which trades material performance for speed to achieve an optimum mix.

Another critical difference between automotive and aerospace materials is the customer. Buyers of aircraft are very sensitive to the operations and support cost of the system and can be more easily persuaded to see the benefits of new materials in reducing the use-cost of the vehicle. Automotive buyers are removed from the design and engineering of the vehicle and are currently not perceived to be interested in the materials content of the vehicle unless there is a great deal of other value-added benefit.

## **Economic Perspective: Automotive vs. Aerospace**

- **Lightweight Premium**

  - AS: Customer will pay high premium to achieve mission goals - weight driver

  - AM: Customer indifferent to weight, CAFE is weight driver

  - AM: Weight premium is based on constrained optimization of product mix objective, profit, position in weight class

- **Manufacturing**

  - AS: Low production volume -low tooling and facilities cost

  - AS: Minimum process control - maximum material control

  - AM: Trade material control for maximum process control

  - AM: Inspection traded for Total Quality Control

- **Aerospace customer pays R&D, manufacture, and O&S**

  - More long-range view - mission objectives drive weight premium

- **Customer more sensitive to initial cost than O&S cost**

  - Minimize costs to satisfy regulations

The cost effective use of new materials is closely coupled to the production volume of interest. Fortunately, new materials use favors low production volumes which is the current trend in the automotive industry. Traditionally auto-makers have favored mass production and long product lifetimes. The current trend is to produce fewer copies of a larger proliferation of products for a shorter lifetime and hence capture a larger share of the overall market. However, the low volume objective of low capital investment and quick lead-time come in direct conflict with the high engineering risks associated with new materials. It is also difficult to mobilize the automotive industry away from its current orientation, high production rate and low manufacturing flexibility, towards higher flexibility and lower production rate.

## **Production Economics**

- **Production Volume**

Range: 10,000 to 1,000,000 /yr

Trend: 10,000 to 100,000 /yr

- **Low Volume Objectives**

Fast product response - short lead time

Low tooling and facilities investment

Low engineering cost - low technical risk

- **Current technology oriented towards high volume**

High production rate

Low flexibility

Structural composites offer potential tooling investment reductions when compared to a functionally equivalent steel structure. This reduction comes from both the lower number of forming steps and the potential to form highly integrated structures from a single molding. However, the long cycle times of most composites processes, which scale with the size of the part, require optimizing the level of integration. As the level of integration increases, the size and complexity of the part may increase the cycle time such that the tooling investment, required to meet production volume, eliminates the cost benefits over steel weldments.

Currently, however, the high engineering cost of implementing composite materials in high production volume automotive applications, more than offsets the design and tooling savings. New technology, such as composites, are best implemented in small incremental steps. Low production volume vehicles, where premiums are often paid for improved performance and the production risks are lower, are excellent platforms for introducing new technology. On higher production volume systems, "bolt-on" applications which can be made transparent to the assembly line are low risk avenues for new technology as well. However, on high production volume platforms, the performance premiums paid are much lower than specialty niche vehicles. Low risk applications for new materials systems are the only way automotive producers can gain manufacturing and engineering design experience necessary for wide spread acceptance.

## **Composite Materials Production Economics**

- **Lower tooling cost options compare to metal processes**

- One-step process

- Opportunities for parts integration

- **New technology requires high engineering investment**

- Small incremental steps

- Very low production volume

- Small, low-risk components - "bolt-ons"

- No manufacturing or engineering experience base

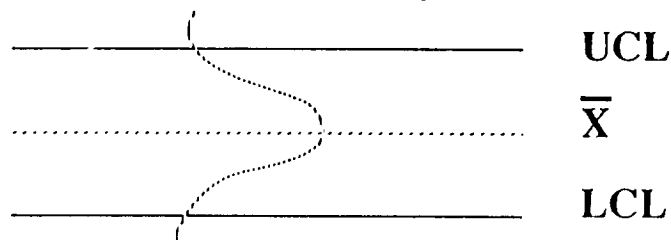
In high volume production, reliable high quality output is achieved through process control. The process needs to be “in control” such that the majority of the product variation is due to random non-controllable events which lie well within the tolerance limits of the design. The variations in material properties which occur in composites must not affect the reliability of the product. In the aerospace industry this is insured by diligent inspection steps and by using expensive high quality materials. In the automotive industry low cost materials are used in high speed, highly controlled processes with enough “over-design” to make up for variations in material properties.

For example, aerospace composites are typically made through the hand layup of pre-impregnated fiber tapes. These tapes are carefully made and characterized so that the fiber alignment and wet-out are well controlled. Unfortunately the high cost of the materials and the lack of control over the manual layup process result in very high product cost. Many of these companies are interested in resin transfer molding, RTM, due to its faster cycle times and lower materials costs. However, there is not enough control over the fiber orientation and fiber wet-out to insure high quality. Thus the research and development effort is aimed at improving the control in RTM.

On the other hand, the automotive industry does not need to derive the highest level of material properties; rather it needs to achieve reliable control over the process for predictable properties. Thus the thrust of automotive structural composites research and development is to achieve higher production rates and control with acceptable material performance. The automotive industry needs to be able to get the same manufacturing performance from RTM as obtained with SMC only with a significant improvement in materials properties.

## Production Economics

- **Manufacturing control is the critical objective -  $C_{pk} > 1.33$**



- **Material properties controlled by over-design**

Sacrifice weight reduction for control

- **For example with liquid composite molding (LCM) vs. other FRP processes**

Aerospace applications - Design LCM to same control as hand lay-up at faster rates.

Automotive applications - Design LCM to same control as SMC at lower rates

In order to illustrate the process by which new materials are introduced into the automobile, consider the substitution of steel with fiber reinforced plastic. For example, consider a steel hood being replaced by a compression molded SMC hood. The basis for the material change is most likely to reduce vehicle weight. The manager of the vehicle program will pay a penalty for eliminating weight. The penalty is estimated by assessing the need to remain in a given weight class against production volume and profitability constraints. CAFE regulations limit the number of vehicles which may be sold in a given weight class which often adversely affects profitability. Reducing the vehicle weight will enable the producer to increase the number of vehicles in desired weight classes.

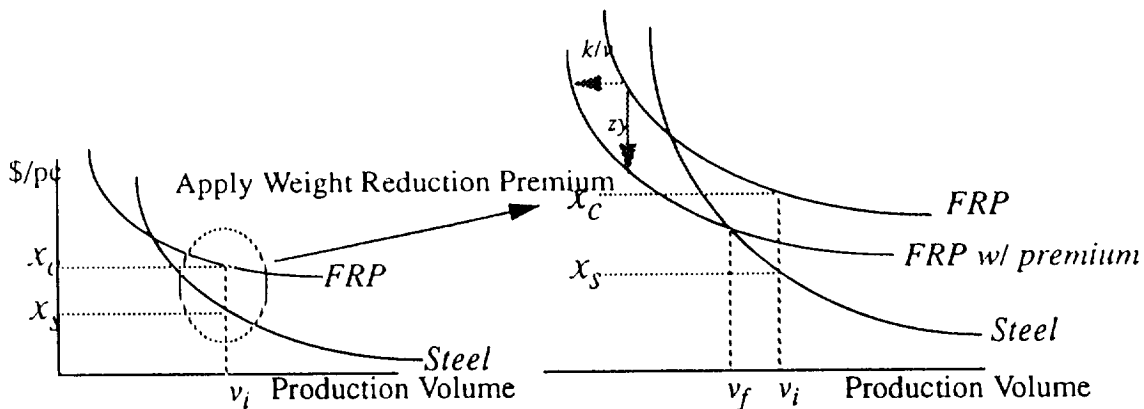
### Example: Steel vs. FRP

- Structural application needing lower weight

Steel part costs  $x_s$  and weighs  $w_s$

FRP part costs  $x_c$  and weighs  $y$  less than the steel part

Program will spend  $z$  \$/lb saved for lower weight and or invest  $k$



There are two main strategies behind the implementation of new technology in automotive products. In the past, compliance with regulatory constraints has been one of the most significant driving forces behind the development and implementation of new automotive technology. This type of driver will, however, limit the “enthusiasm” for the development of the technology. Since the producer is satisfying a standard, their preference for performance is binary; they will only pay to satisfy the standard not to exceed it. This means that the most conservative route will be taken to achieve the goal. The timing of the development process is usually set by the regulators and thus must be met. To minimize the risks of meeting the timing plan, new inventions must be limited to as few as possible.

One of the most effective means of developing the new technology at minimum risk is to buy it from a supplier. Unfortunately this often means that competitors are able to purchase the technology as well. The other driver for implementing new technology is to use it for achieving world class products. This is a situation where the producer is potentially willing to pay for superior performance if it is perceived that value is directly added to the product yielding higher profits.

### **Attitudes Towards Enabling Technology**

- **Helps future products satisfy expected CAFE standards and other regulations**

  - Achieve goals at minimum investment

  - Zero risk of achieving goals - minimize number of inventions

  - Buy technology from supplier

  - Timing set by regulation - Can drive initial premiums higher than long term goal

- **Helps products achieve world class status**

  - Attempt to develop technology in-house or with supplier partnership

  - Risk reducing pilot programs

There are numerous examples in the past where new materials technologies have been implemented in products to achieve both better performance and regulatory compliance. High strength steels have been incorporated into the vehicle structure to achieve approximately 10% weight savings over mild steel. However, initially many obstacles had to be overcome as body and assembly operations learned how to form and weld these “newer” materials. Galvanized steel was introduced in order to reduce body corrosion and improve durability. This enabled U.S. made vehicles to compete better with Japanese vehicles whose superior paint technology provided improved corrosion protection.

Ford has started manufacturing aluminum block engines both for their improved fuel efficiency, weight savings, and for the market appeal. Casting aluminum blocks presents many technical challenges for a company who has traditionally used iron blocks. The challenges are both in adopting a whole new casting technology as well as learning to machine dissimilar metals.

Forged connecting rods are being replaced by powder metal, PM, rods on a regular basis. There are many advantages to the PM rods. They are delivered to the machining and assembly line in a closer net shape than the forged rods. There is better control over the mass variation leading to easier balancing. The cap is easily “cracked” from the rod blank providing a perfect mating surface and eliminating several machining and grinding operations on mating faces. The pin-end aperture is formed into the blank eliminating a drilling operation. All of these cases represent new technology which was essentially compatible with the basic manufacturing infrastructure, at some level of the overall process, of the automotive producer. The last two required the participation of a supplier since the basic forming processes, PM and aluminum block casting, were not traditionally used by the automotive industry.

## **Past Examples**

- **High Strength Steel**

Weight Reduction

- **Galvanized Steel**

Corrosion Resistance

- **Aluminum Engine Block**

Weight Reduction

High Tech Image

- **Powder Metal Connection Rod**

Reduced Machining Investment

Successful implementation of new materials requires that they meet both technical and economic standards set by the specific industry. They must at least meet the performance level of the existing material. Surpassing the basic criteria is only desirable if there is value added to the product which the customer will pay a premium for. It is also very difficult for industries to rapidly shift to a new manufacturing technology successfully. Changing manufacturing technology requires intense capitalization both in equipment and in human resources. New materials which are compatible with the current manufacturing capacity are likely to be adopted quicker.

New materials must also show that they can be processed to give repeatable properties without severely affecting the productivity of the operations. Usually new technology has a higher unit cost, possibly a transient due to learning or volume effects, which must be offset by budgeted premiums. These premiums are usually paid to enable new technologies to be used with low risks. The risk of implementing new technology has to be low so that the development of the entire system is not jeopardized. One of the best strategies for developing new technology for production is to gain experience with low risk incremental applications such as pilots or easily substituted components. The most sought after technology will be that which enables producers to maintain or, even better, attain a competitive position in the marketplace.

## **Conclusions**

- **Technical requirements for new materials**

- Maintain or surpass required performance standards

- Compatible with existing manufacturing technology

- Repeatable properties

- **Economic requirements of new materials**

- Higher cost offset by premium for enabling technology

- Low technical risk

- Affordable and low risk incremental applications

- Critical technology to maintaining competitive standing