# O. Technical Cost Modeling

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## Objectives

- Address the economic viability of new and existing lightweight materials technologies.
- Develop technical cost models to estimate the cost of lightweight materials technologies.

## Approach

- Address the economic viability of lightweight materials technologies supported by the ALM.
- Use cost modeling to estimate specific technology improvements and major cost drivers that are detrimental to the economic viability of these new technologies.
- Derive cost estimates based on a fair representation of the technical and economic parameters of each process step.
- Provide technical cost models and/or evaluations of the "realism" of cost projections of lightweight materials projects under consideration for ALM funding.
- Examine technical cost models of lightweight materials technologies that include (but are not limited to) aluminum sheet; carbon fiber precursor and precursor processing methods; fiber-reinforced polymer composites; and methods of producing primary aluminum, magnesium, and titanium and magnesium alloys with adequate high-temperature properties for powertrain applications.

## Accomplishments

- Assessed comparative cost of alternative manufacturing technologies for the composite-intensive body-in-white (BIW) structures.
- Assessed lightweighting opportunities for fuel cell vehicles.
- Assessed carbon-fiber-reinforced polymer (CFRP) matrix composites potential for the automotive industry.

## Future Direction

- Estimate the impacts of the ALM for the fiscal years FY 2000–2004 and also aid in the formulation of mid-term and long-term goals for the ALM.
- Continue individual project-level cost modeling to identify specific technology improvements and major cost drivers that are detrimental to the economic viability of these technologies.

## Comparative Cost Assessment of Alternative Carbon-Fiber-Reinforced Composite BIW Manufacturing Technologies

This task focused on the relative cost-effectiveness of competing carbon-fiber-reinforced, polymer (CFRP) composite, BIW manufacturing technologies. The part under consideration was an upper dash panel weighing about 1.9 kg. Of a total of six competing manufacturing technologies under consideration, three were based on the compression molding and long fiber injection (LFI) processes. The process by Krauss-Maffei was selected as the LFI process. Two carbon-fiber sheet molding compound (SMC) materials for the compression molding process considered were Quantum composites and HexMC by Hexcel Corporation. The former carbon-fiber, sheet molding, SMC material has recently been used in Dodge Viper for the windshield surround, inner door panels, and fender support system applications. Of the three remaining manufacturing technologies, fabric preforms using CompForm technology and prepregs besides the programmable powder preform process (P4)/structural reaction injection molding (SRIM) process were considered.

With the limited data available directly from the suppliers where most of these technologies are still in the development stage, LFI appears to be the most cost-effective technology among the six competing technologies considered here. As shown in Figure 1, the costs of parts produced by the six technologies range from $28.12 to $129.18, and the cost-effectiveness of various technologies, in decreasing order, is as follows: LFI, P4/SRIM, Quantum, CompForm, HexMC, and prepreg. The high scrap rate (i.e., 10–30%) of material that costs $20/lb causes HexMC and prepreg technologies to be the least cost-effective among the technologies considered here. The part cost per pound ranges from $6.45 to $35.29, considerably higher than the weight savings premium of $1–$4/lb accepted by the industry. Material dominates the overall part cost distribution in all cases, followed by labor, capital,

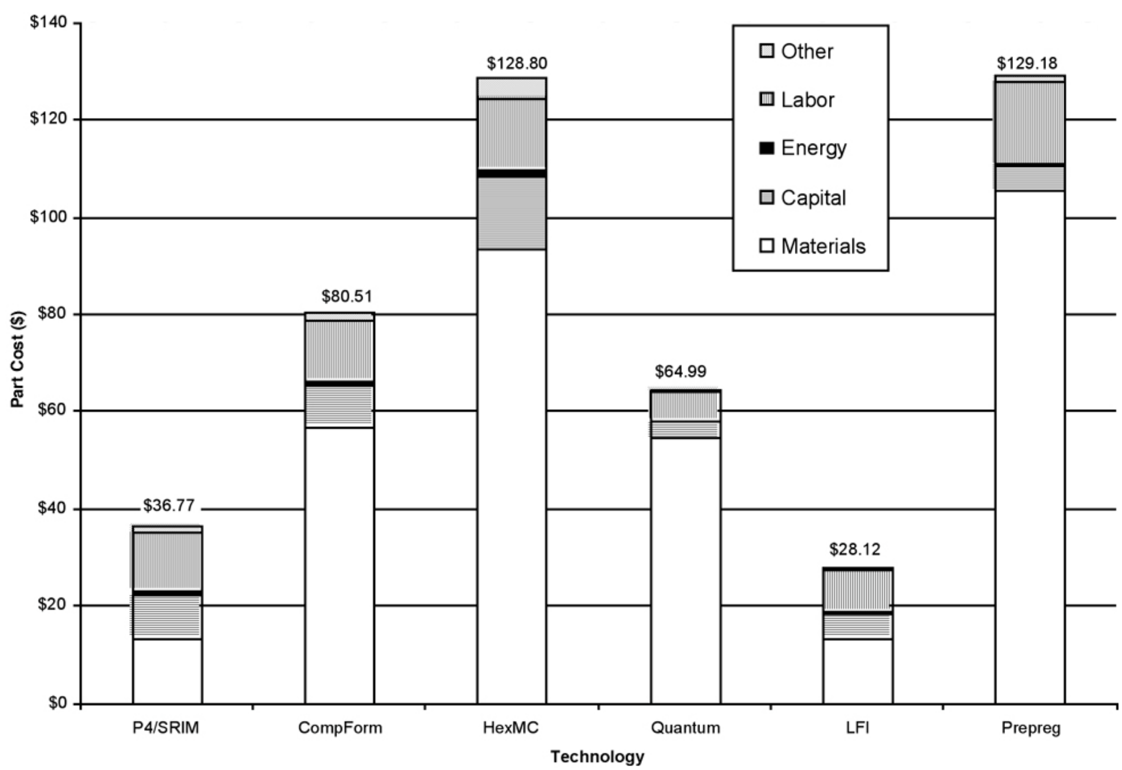


**Figure 1.** Baseline upper dash panel cost distribution.

and energy, where the last component is comparatively less significant to overall part cost. The share of material to part cost was found to be in the range of 37% to 84%, where the lower- and upper-end values correspond to P4/SRIM and Quantum technologies, respectively. Capital cost is greatest for HexMC technology due its 13-min-long molding cycle and the high molding pressure used. The labor costs of P4/SRIM, CompForm, HexMC, and prepreg technologies are higher than the other two technologies and similar to one another because of these technologies' higher cycle times at the charge preparation/preforming step.

It appears that significant technology enhancements, beyond drastic carbon fiber material cost reductions, will be necessary for the four non-chopped carbon fiber technologies to be cost-effective. For example, LFI's automated single-step operation, low molding pressure, and chopped carbon fiber use cause it to be most the cost-effective technology. Even with significant increases in major baseline parameter values, this technology was still found to be economically superior to five other technologies. With its capital costs higher than LFI's and its performing cycle time, P4/SRIM is the second most cost-effective technology. Quantum's lower cycle time gives it the potential to be competitive, but it would require a significant reduction in carbon fiber material cost. Quantum's part cost is estimated to decrease by $4.20 per $1/lb decline in carbon fiber material cost. The main drawback to the CompForm technology is its high preforming cost—higher than P4—due to its higher fabric cost and preform scrap rate. A 44% reduction in carbon fabric cost can lower part cost by 30% using this technology. High material cost, charge preparation scrap rate, and molding cycle time are some of the potential drawbacks of HexMC technology. Currently under development are polyester-based HexMC materials requiring no staging and a significant lower molding cycle time of 1.5 min, which will likely improve its cost-effectiveness. Advantages of low-cost press molding of prepregs can only be cost-effective with significant reductions in prepreg cost and charge preparation scrap rate. The use of cheaper, unidirectional carbon material of more than 24K will significantly lower the prepreg cost.

## **Lightweighting Opportunities for Fuel Cell Vehicles**

This task examined the lightweighting opportunities for midsize passenger, direct hydrogen, fuel cell vehicles to determine whether this would facilitate the early commercialization of fuel cell vehicles. The current fuel cell powertrain is heavy and expensive, so it is interesting to examine whether at the expense of lightweight BIW materials alone, the fuel cell vehicle penetration rate can be enhanced. The commercial viability of fuel cell vehicles is examined in the context of several advanced lightweight BIW material options [i.e., ultra light steel autobody (ULSAB), stainless steel spaceframe, aluminum unibody, aluminum spaceframe, glass fiber reinforced polymer composites, and CFRP composites] alone, as well as in combination with improvements in the fuel cell powertrain. A detailed 35+ vehicle components level automotive system cost model was used to estimate the lightweighting opportunities for fuel cell vehicles.

A midsize direct hydrogen fuel cell vehicle cost is estimated to be 3.88 times higher than the conventional vehicle. A heavier powertrain in fuel cell vehicles causes an increase in the body subsystem weight by 22% and contributes to 3.34-fold increase in the vehicle cost. It is estimated that the weight and cost of current fuel cell vehicles need to be reduced by 41% and 74%, respectively, for the vehicles to be competitive with the conventional vehicle today. Several lightweight BIW materials not in widespread use today have vehicle-weight-reduction potential in the range of 4–17%, considerably less than the desired goal. The lower- and upper-end of this weight reduction range correspond to ULSAB and CFRP BIW material, respectively. Even CFRP, having the greatest weight savings potential, will reduce vehicle costs only by 11%, far less than the 74% cost reduction needed to achieve commercial viability.

As one would expect, improvements in fuel cell parameters such as specific power and cost would have greater impacts than lightweight materials. Alone, a reduction in fuel cell cost by 78% ($200/kW today vs $45/kW 2010 DOE target), would lower the current cost of fuel cell vehicles by 57%, whereas a 60% BIW weight savings with

CFRP would lower vehicle cost by 12%. Only a substantial vehicle weight reduction can be achieved with the improvements in fuel cell specific power. A 40% improvement in fuel cell specific power is necessary to achieve the 2010 DOE target, but this level of improvement will result in vehicle weight and cost reductions estimated to be 24% and 17%, respectively. Although lightweight materials alone may not be able to achieve the desired vehicle weight and cost goals, they are definitely anticipated to aid in the early commercialization of fuel cell vehicles by imposing less restrictive requirements in fuel cell improvements. For example, for a 30% reduction in vehicle cost, necessary fuel cell cost improvements can be reduced by 3.5% and 10% with the use of ULSAB and CFRP BIW materials, respectively. Impacts of lightweight materials were significantly higher in the case of fuel cell specific power because both are directly related to weight. For example, for a 15% reduction in vehicle cost, necessary fuel cell specific power improvements can be reduced by 7.6% and 24% with the use of ULSAB and CFRP BIW materials, respectively.

Vehicle weight reduction will definitely help but alone may not be sufficient for early commercialization of fuel cell vehicles. The role of lightweighting for fuel cell vehicles is anticipated to be at least very similar to that observed for conventional vehicles in maintaining weights despite the introduction of various weight-adding vehicle technologies during the past two decades. The research and development in vehicle lightweighting will be more critical for fuel cell vehicles—extending well beyond the powertrain components—because vehicle weight and cost challenges pose a serious hurdle for the commercialization of fuel cell vehicles today.

## Potential of Automotive Carbon Fiber Reinforced Polymer Composites

CFRP composites, with weight reduction potential of 50–70% and a considerably higher strength-to-weight ratio compared to conventional steel, provide a tremendous potential in automotive applications. To date, the use of this material has been limited to upper-end, high-performance, price-premium, niche vehicles limited to a production volume of less than a thousand per year in most applications. Several concurrent research and development projects are currently under way, but it is not clear when, or whether, this material, will find widespread use in commercial automotive applications. Manufacturing cost is one of the major concerns for original equipment manufacturers (OEMs) considering any material substitution, and this, along with the material's ability to meet long-term technical requirements and its manufacture for the automotive environment, is cited as the most significant challenge for its automotive application today. Consequently, this task examined the existing cost studies of CFRP and explored the factors associated with the high cost of material to determine under what circumstances and at what future point this material may become suitable to be used widely in automotive applications.

Most cost studies to date have focused on the BIW application at large-scale production volumes, comparable to conventional steel, where part consolidation is maximized to make the part at least cost. These studies confirm that cost-effectiveness of BIW can be achieved at a production volume less than 100,000 parts/year, and material cost and cycle times are detrimental to the economic viability of CFRP today. High material cost is the main factor at a larger production volume, and carbon fiber is the main contributor to material cost. Lowering carbon fiber cost would not only improve CFRP competitiveness in terms of per-part cost at a given annual production volume, but it would also increase the annual production volume range at which it stays competitive. At a production volume range of less than 125,000 parts/year, carbon fiber price in the range of \$3–\$5/lb will be sufficient to reach cost effectiveness. ALM work to develop new carbon fiber manufacturing technologies suggests that these price targets are achievable. Carbon fiber prices of less than \$3/lb, a requirement indicated by several studies, may not be necessary to achieve the CFRP cost-effectiveness at a relatively large production volume if optimized designs offering a significantly higher level of weight reduction can be achieved.

Most fabrication technologies for CFRP are anticipated to be similar to those used for glass-fiber-reinforced polymer composites (GFRP), but they are yet to be demonstrated. Most of these technologies are not effective at scaled-up production volumes with high cycle times, posing one of the major barriers to their scale-up and, thus, cost-effectiveness. A recent ORNL cost assessment of six competing high-volume processing methods (as discussed above) indicates a manufacturing cost range of \$6.45 to \$35.39/lb, significantly higher than the $2.50/lb needed to be in contention with aluminum in certain automotive applications. The popularity of GFRP SMCs has been recently demonstrated for CFRP as well, but these finished carbon-fiber-based materials technologies appear to be more expensive than direct-chopped fiber technologies and do not provide any major subsequent processing benefits. A recent study has rightly pointed out that a significant reduction in process costs that is achieved through a high degree of automation at all stages of manufacturing and that reduces the number of intermediate products in the process chain, can do much more to change the current viability of CFRP than a decrease in carbon fiber prices. The key to bringing CFRP into automotive usage is to advance today's enabling process technologies and improve the vertically integrated supplier structure.

Due to higher weight reduction potential in assembled BIWs, CFRP is competitive at significantly higher production levels when considered system-wide than when considered in part-by-part substitution. Because it is relatively less risky, the part-by-part substitution is likely to continue in the foreseeable future, and the industry will gain experience needed to feel comfortable with this material. It will be at least a decade or more before one will find CFRP in any large-scale commercialization of automotive BIW structures. However, the focus of past cost studies on the viability of CFRP structures at large production volumes may be contrary to the latest trends of platform sharing and low-production-volume vehicle models. Of all vehicle models manufactured in 2003, 72% (or 2.1 million units) of car models and 69% (2 million units) of truck models were in the production volume range of less than 100,000 vehicles/year. These trends have allowed the mixing of lower-volume "differentiating" technologies with higher-volume "standardized" technologies to increase market attractiveness and lower costs. CFRP is definitely a promising candidate for differentiating standardized vehicle platforms.

Consideration of life-cycle costs that appropriately assess the cost-effectiveness of lightweight materials is not prevalent in the automobile industry's materials selection. It is, nevertheless, imperative to consider in this analysis the parameters that affect vehicle operation stage costs, for example, fuel economy improvements and fuel costs due to vehicle lightweighting. The sensitivity analysis of major parameters indicates that on a life-cycle cost basis, the cost-effectiveness of CFRP at a higher volume of 250,000 parts/year can be attained within the first vehicle life in all cases, unlike on the basis of manufacturing cost alone. As shown in Figure 2, a fuel price increase to $3/gal (100% increase from the base price) will allow the life-cycle cost equivalence to conventional BIW steel achieved at about 7 years; however, the fuel price as high as $4.50/gal (about 200% increase from the today's price) would not provide the cost-effectiveness of CFRP on the basis of manufacturing cost alone. Lower carbon fiber price of $3.3/kg or CFRP manufacturing cost decline by 25% at a large production volume will facilitate in achieving the life-cycle cost equivalence to steel within the first 10 years of vehicle life. The weight reduction factor of CFRP is critical, a lower 55% BIW weight reduction potential than optimized 67% weight reduction potential design at a production volume of 100,000 parts/year would move the cost-effectiveness from the first year of vehicle life to beyond 12 years of vehicle operation. Life-cycle cost consideration would allow not only to determine when the life-cycle cost equivalence can be achieved but also extends the annual production volume range of the CFRP cost-effectiveness. Whether material suppliers, component suppliers, and automakers must respond to life-cycle cost issues remains to be determined. Ultimately, their

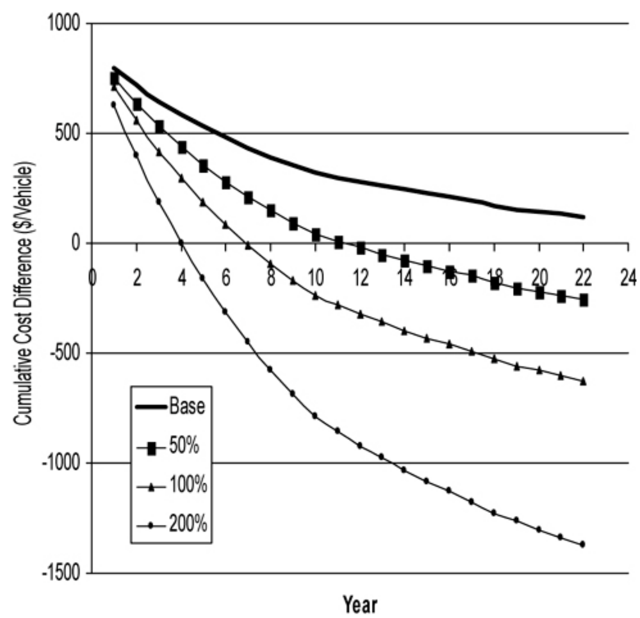


**Figure 2.** A comparison of CFRP BIW cumulative life cycle cost impacts of different fuel price scenarios.

response will depend on their ability to benefit from these savings combined with consumer demand and the legislative environment.

It is unlikely that the large-scale commercialization of automotive CFRP parts will happen any time in the near future due to high material cost and a lack of high-volume processing technologies; challenges that the industry faces comparatively are more for the higher production volume range. Until then the product differentiation aspect of the platform-sharing will promote the CFRP material substitution in niche, low-volume, premium performance vehicles. The performance market segment of the aftermarket industry continues to grow by providing the customization preference to the consumers to compete with the entrance of so many newer vehicles equipped with modern engine and handling technology into this segment. The low-production-volume market size appears to be large enough to maintain the viability of the CFRP industry during the initial market penetration phase. There are several other competing lightweight materials such as GFRP and aluminum, including high-strength steels with the industry experience comparatively high on the learning curve, which would pose obstacles in the large-scale penetration of CFRP automotive applications. Unless there is a demand for lower vehicle weight with higher strength-to-weight ratio precipitated by events such as an extremely high fuel price increase, high fuel efficiency and low emissions standards, and alternative powerplant technologies (e.g., fuel cells) requiring a considerable reevaluation of complementary lightweight bodies, it would be difficult to justify CFRP purely on the economic perspective alone. This material could produce a major change in automotive engineering in the future, but major sociopolitical shifts will be needed to bring about a carbon fiber-based synergistic change.

## **Publications**

1. "Magnesium for Automotive Applications: Primary Production Cost Assessment," *Journal of Metals* (November 2003).

2. "Life Cycle Impacts of Automotive Liftgate Inner," accepted for publication in *Resources, Conservation and Recycling*.