The Significance of Production Cost Inputs in Regional Technology Choice:

Composite Automotive Body-In-Whites in the US versus China

by

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Abstract

Nations seek to influence the technology decisions of multinational firms producing within their borders for many reasons. These reasons range from a nation's desires to maximize its competitiveness in the global marketplace to a nation's desire to improve the social welfare of its citizens. Alone by understanding the forces driving multinationals' decisions, can nations develop means to impact those decisions. Market supply, market demand, individual interests, group interests and government policy all affect the technological decisions of firms' managers and engineers. This work models the cost of automotive body-in-white production in the United States versus the People's Republic of China. Three body-in-white materials are evaluated for each country: carbon-reinforced composites, glass-reinforced composites, and steel. Based on the results, insights are sought on the significance of production costs versus other factors in driving the extent of composite body-in-white vehicle production in China versus in the U.S.

Composite body-in-whites are, according to the results of this thesis, produced less frequently in both the U.S. and China than would optimize manufacturing costs. Composites have a production cost advantage over steel for more U.S. scenarios; however, interest in composite body-in-whites is greater in China. Several qualities of the Chinese market help explain this dichotomy between production cost implications and in-country actions. Concerns of part tolerances, surface appearance, worker safety during processing, and legal ramifications of non-conventional crash mechanisms do not hold the same weight in China as they do in the U.S. Greenfield investment opportunities are many in China, and China is known for a willingness to experiment. In contrast, the U.S. auto industry is plagued with embedded capital costs and powerful stakeholders in association with steel. The interests of firms, nations, and individuals do not always overlap. The results of this thesis, however, suggest that it would be in the interest of all for greater investment to be made in composite body-in-white production in the U.S., and for experimentation in composite body-in-white production to continue to be encouraged in China.

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Freud writes of two essentials to living life: to love and to work. The later is, for me, both nothing and impossible without the former.

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My brother, Geoffrey S.H. Fuchs, was the person in this world, from a very young age, I cared about the most, and my longest companion, covering 22.5 of my 25 years.

On August 3, 2002, he offered me a second chance at life with his.

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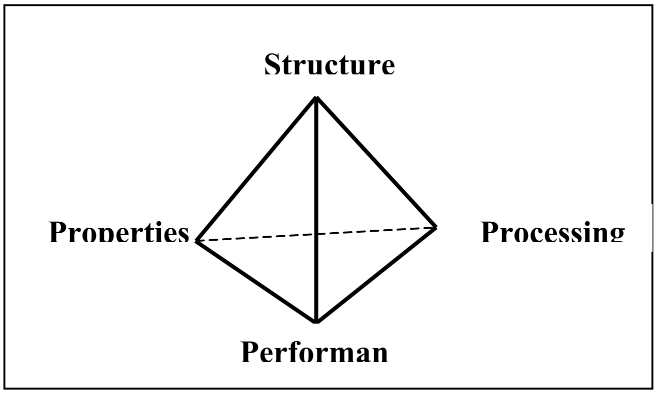
1. The Forces Driving Technology Choice

The quandaries surrounding technology choices and their consequences have confronted stakeholders ranging from scientists and engineers, to economists and investors, to political scientists and policy-makers. Each discipline has a different take on the issues and the domain of the problem. Conventionally, an engineer focuses on designing to meet function or performance requirements. A micro-economist concerns herself with balancing production costs versus consumer utility for product characteristics. A macro-economist hones in on the role technology choices can play in regional or national economic growth. A political scientist involves himself in the consequence of human and institutional forces in technology choice as well as how those can be harnessed towards social or national objectives. The general approach of each of these three fields – engineering, economics, and political science – to technology choice is introduced below to lay a common groundwork for readers.

Arguably most intimate with the process of technology choice, especially at the micro level is the engineer. Webster's Third New International Dictionary defines "engineering" as "the science by which the properties of matter and the sources of energy in nature are made useful to man in structures, machines, and products" (Webster 1986). Understanding the drivers behind technology choice requires an understanding of the mental model with which the engineer approaches and solves a given problem of making "the properties of matter and the sources of energy in nature useful to man. Some of the earliest work on the engineering process, is by Schumpeter. Schumpeter models technological change as a linear process with three stages: invention, innovation, and diffusion. The invention process encompasses the generation of new ideas. The innovation process consists of the development of new ideas into marketable products and processes. During the diffusion stage, new products and processes spread across the potential market. Basic research, undertaken with no particular applied objective in view, was followed in Schumpeter's linear model by applied research and development, and then finally by commercialization. (Schumpeter 1934). In 1982, Nathan Rosenberg introduced the now more widely accepted concept of technological change not as linear, but rather as cumulative, interactive, and characterized by feedback. Some innovations are purely accidental. Others evolve by putting known ideas to different uses. Developments in applied research can initiate new fields of basic science. The better the knowledge and communication networks, the better the model functions. (Rosenberg 1982)

Neither Schumpeter, nor Rosenberg, nor the later developments on the subject by their collegues, seem to truly step into the engineer's mind and bring out the drivers behind particular choices. Better insights into the drivers behind an engineer's choices can be found within engineering textbooks themselves. The introductory textbook used in the M.I.T. core materials science and engineering (MSE) class poses the domain of the material engineer's problem as a four-cornered tetrahedron (Allen 1999). At the four corners of the tetrahedron are structure, properties, performance, and processing. Each of these categories represent a set of category-specific requirements to which the engineer's final design (and materials selection) must conform. See Figure 1. The tetrahedron is used to depict that not only is it vital for the engineer to adhere to the structure, properties, processing, and performance requirements of any design, but that all of the elements are directly connected to each other, such that changes and choices in any one requirement has direct material consequences for both the requirements and technical choices of the other three.

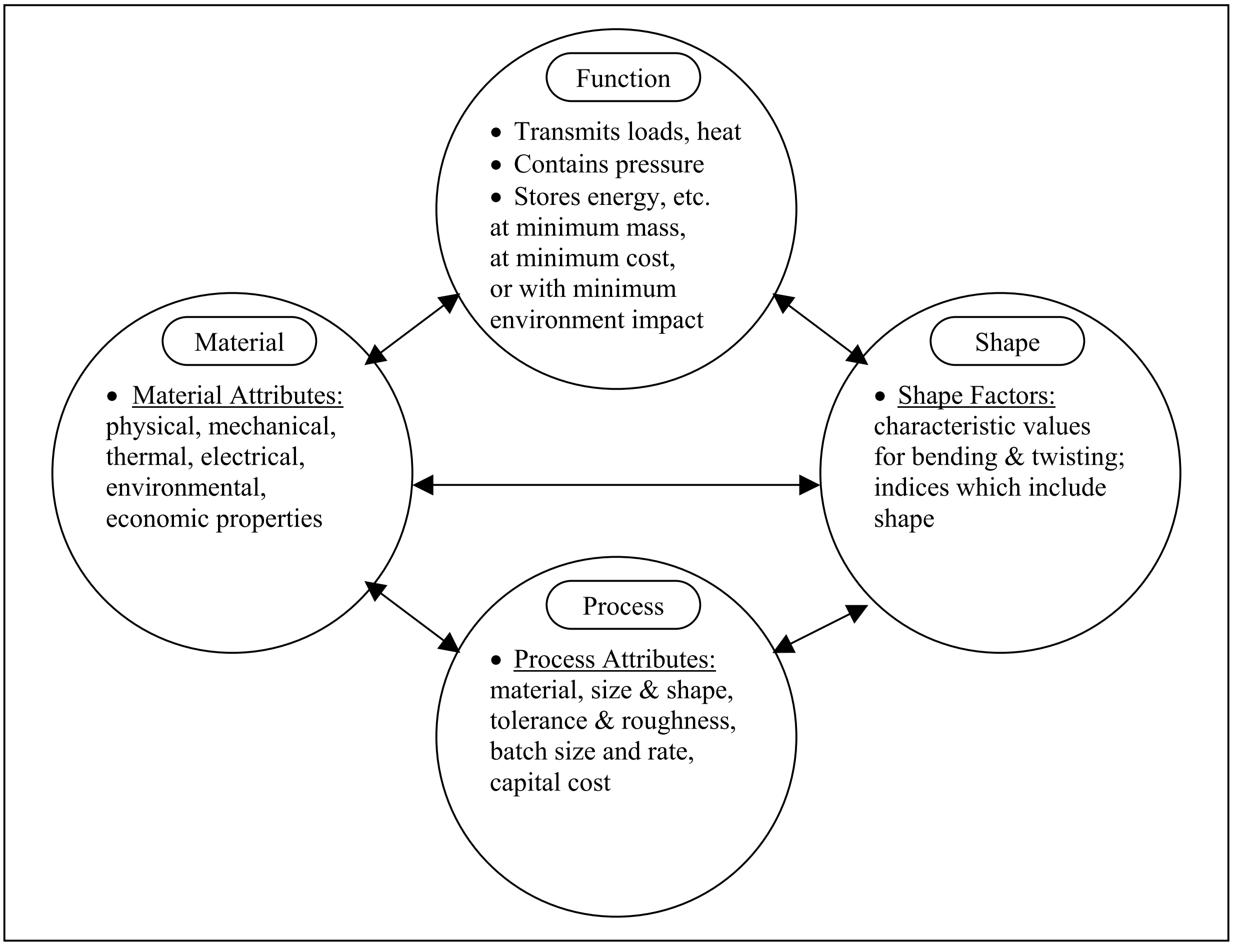
Figure 1: The Materials Science and Engineering Tetrahedron



Source: Allen, S. and Thomas, E., *The Structure of Materials*, John Wiley and Sons, Inc., New York: 1999.

A similar breakdown of the engineer's problem is provided by Michael Ashby, from the Cambridge University Department of Engineering, in reference to mechanical design. Ashby separates the interacting forces an engineer must balance into function, shape, material, and process (Ashby 1999). See Figure 2. Although the interacting requirements to balance might differ slightly for a civil engineer, a chemical engineer, a computer science engineer, or other fields of engineering, the concept of an engineer balancing the properties of matter (or "material") and energy against performance (or "function") requirements against the constraints of processing, structural, or whatever other relevant constraints of the field is potentially applicable to many of the fields. Given that the case chosen for this work focuses on material, mechanical, and processing technology choices for composite BIW technology, engineering problem-approach models potentially relevant for other fields have not been pursued. The relevance of this work's conclusions regarding "technology choice" for such other fields would require additional study.

Figure 2: Strategy for Mechanical Design



Source: Ashby, M. *Materials Selection in Mechanical Design*. 2nd Ed. First Published by Pergamon Press Ltd. (1992). Butterworth-Heinman. Oxford: 1999.

Interestingly, in both the Allen and Thomas and the Ashby models, the origin and definition of the problem is not part of the considerations to be taken on by the engineer. Ashby writes, "Design is the process of translating a new idea or a market need into the detailed information from which a product can be manufactured"(Ashby 1999). Neither Allen and Thomas's nor Ashby's model consider the interactions between properties, structure, processing and performance, and the exogenously portrayed "new idea" or "market need". In practice, the engineer's problem is continually re-defined through the interactions between the engineer and his environment, and the technical choice finally put into practice isn't always hers.

Work began to come out of the engineering fields to more systematically incorporate "market need" into technology choices in the early 80s. In 1985, the Materials Systems Lab at MIT exposed the insufficiency of economic approaches to technology choice, especially, materials selection (Field 1985). While economists saw the choice of one material over another to be a trade-off simply in the cost and performance of the material, the consequence of such material choices on the manufacturing system are actually far more complex. Changes in materials have ripple effects throughout the manufacturing system, including tool costs, tool lifetimes, cycle times, machine costs, energy consumption, and labor requirements. Changes in design likewise affect such variables throughout the production process. Only by modeling the entire manufacturing system so as to include the fundamental linkages between material and design and the variables above, do the consequences of product and process choices on final cost become transparent. The models built to contain these linkages have come to be known as technical cost models (Busch 1988).

Work was also done using Keeney-Raiffa multiattribute utility to aid in technology choices in materials selection, engineering team design decisions, research management, and new product and new material introduction through the identification of preference functions (de Neufville 1990). In the case of choosing whether to introduce new products or materials to the market, and if so, at what price, producers obtain their customers' multiattribute utility functions. The analysis then constructs an isovalue line through the properties of the material currently used for some application. Several instances have been observed in which the analysis demonstrated that a new, technically superior material simply could not be produced at a competitive price. For example, in one instance, a manufacturer was able to determine that advantages in lower weight did not compensate for the extra costs required to produce a given material. In another instance, a producer was able to estimate how high she could price a new material so that it would be at the maximum price which still offered greater utility to the potential user(de Neufville 1990).

The economics discipline began to address the interface between technology and economic forces also in the early 80s. Initially, work at this interface was primarily within non-dominate schools of thought. At the macro level, J.A. Schumpeter's work (already referenced earlier), The Theory of Economic Development, placed importance on the role of technological innovation in long term economic cycles (Schumpeter 1934). The only approach addressing technology choice from the micro side was A.K. Sen's, *Choice of Techniques*, which sought to explain the choice of technology in terms of the orthodox two-factor production function of neoclassical economics (Sen 1968). The other relevant works dealt with a long-running debate about whether or not there are biases in the direction of technological change (e.g. towards capital production methods) (Hicks 1932), (Salter 1960), (Habakkuk 1962), (Saul 1970), and (David 1995).

In mainstream schools of thought, however, technology continued to be treated in economic theory as an important factor of production, but exogenous to the economic system. Kelvin Willoughby (1990) writes, "The state of technology in the economy was seen as something which was "given" at any particular period, changing from time to time as "breakthroughs" emerged from the supposedly independent activities of scientists and engineers" (Willoughby

1990). In 1982, Nathan Rosenberg's work, *Inside the Black Box: Technology and Economics*, began to develop a macro-economic theory taken up by the mainstream with technology as an endogenous factor (Rosenberg 1982). Micro-economic work on technology choice continues to appear to be lacking.

These economic forces do not always act directly on the engineer, nor does the engineer always get to make the final technical choice. Business-strategy studies have expressed strong interest in the importance of managerial decisions as determinants of technological innovation (Burgelman 1988) (Twiss 1986) (Granstrand 1982), and publications in economics have likewise since addressed this perspective (Coombs 1987). In his 1972 article, "Economic Man and Engineering Man: Choice of Technology in a Low Wage Country", Louis Wells argues that the simple combination of production functions and factor costs is inadequate in explaining the complex factors that influence a manager in his choice of production techniques. Wells suggests that, at least in a low-wage country, a manager's choices of technology are driven by two objective functions, that of the "economic man", looking to minimize costs, and that of the "engineering man," leading to more sophisticated technology. When price competition is the rule, the objectives of the "economic man" seem to override those of the "engineering man." However, when the firm has a monopolistic advantage, there is a reduction of the pressure on the firm to minimize costs to survive; the goals of the "engineering man" are allowed to move the firm to a more advanced level of technology than the "economic man" would choose. (Wells 1972).

Technology choices are made by humans, and as such are driven neither by technical factors nor by economic factors alone. Political science provides both a structured approach to the "human factor" and to institutional forces, as well as an accepted forum for discussing "failures" in market and institutional forces. Unstable property rights (Long ; Hettinger 1989; Braga 1998; Heller 1998; Viscusi 2000), information asymmetries and imperfect consent (Groth 2000; Morgan 2000; Viscusi 2000), imperfect competition and monopoly or monopsony (Hart 2000; Viscusi 2000), adverse selection and tipping, externalities and public goods problems (Coase 1960; Carvalho 1999; Gholtz 1999-2000; Reinsch 2000; Viscusi 2000; Keller 2001), and coordination problems (Murphy 1998) can all cause the market to fail to produce the most economically efficient outcome. See Table 1. Political institutions can also fail to promote the most desired outcomes. Concentrated interests tend to be over-represented and diffuse interests under-represented (Olson 1982). The direction of regulation can be steered by industry and designed and operated primarily for its benefit rather than for the public good (Stigler 1971). Costs of bargaining and acquiring influence can outweigh costs of inaction, and prevent groups from taking action (Milgrom 1990). See Table 2. Willoughby writes, "[Economists until the early 1980s] generally assumed that, under ideal conditions, normal economic forces would lead to the adoption of optimal production systems, given a particular stock of technology available at any particular time" (Willoughby 1990). The ability of drivers of technology choice to, left to themselves, lead to "optimal" solutions, has been shown not to be true, from an economic perspective, and, importantly, also from a social perspective.

Table 1: Political Economy and Market Failure

Sources Market Failure	Some Examples from Daily Life at MIT	Some Daily Life Solutions	Competing Values in Examples	Some Real Policy Examples
Unstable Property Rights	Parking space on streets in snowstorm Lounge in dorm Living in a triple	Private Claim/Public Plow House Gov/ Manager Colonization/ Negotiation	Fairness	Napster, LaMacchia HIV and CIPRO State Street & Amazon Gene patents
Imperfect Competition	Food services Overlap group Books	Regulation and oversight Trucks, Catering Cooperative + On line competition	Safety	Bell/ATT/MCI Microsoft Airbus-Boeing
Externalities	Smoking Loud Music Cats	Mitigation/ compensation or centralized regulation or force	Cultural values; Fairness	Public broadcasting Air and water pollution Vaccination Security NPT Energy security Basic Research
Imperfect Info & Consent	Food trucks Drugs and Alcohol Human Subjects	Label or Ban Regulate/ Educate/Allow COUHES	Efficiency and choice Cultural values Freedom of inquiry	GMO foods BGH beef and pork Irradiation foods Nuclear power and waste?
Adverse Select& Tipping	Vanishing Dining Halls MIT Medical	Manadatory dining and medical insurance	Social capital Paternalistic concern	Bank Runs Medical Insurance and Genetic Screening
Coordination Problems	Sleeping hours MAC v Wintel Decentralized alcohol regs	Convergence or diversity (distributional conflicts) relocation by jurisdiction)	Fairness; health Mac Values Culture Bexley/Senior/EC	Technical Standards Harmonization of regulations on all above

Source: Professor Kenneth A. Oye, 17.950 Science, Technology, and Public Policy, Cambridge, MA. M.I.T. Fall 2001

Table 2: Sources of Institutional Failure

	Problems	Daily Life MIT Examples	Public Policy Examples	Assorted Solutions
Collective Action Dilemma Olson	Freeriding – public benefits and private costs Underrepresentation of diffuse interests and overrepresentation of concentrated interests	Asking dumb questions in class Frats, alums, and first year housing	Common problems Consumers and export oriented vs. import competing Logrolling and pork barrel	Selective incentives Moral suasion Compensating concentrated interests Straight up and down votes
Regulatory capture Stigler	Limit entry Guarantee market Secure subsidies Shift costs	Sloan TMP SHASS CI B&G Contracting	AMA, ABA CARB ZEV US IGCC Japan Pu Euro diedel Organic foods Clean fuels	Rules on conflict of interest and revolving doors oversight and policing political competition
Bargaining and influence Milgrom and Roberts	Costs of rent seeking and cost of setting up organizations to protect against rent seeking	Student agencies and funding	Lobbies + info distortions (Patriot) + rigidity from efforts to insulate	Above PLUS reduce role of nonmarket institutions
Organizational processes Allison, Simon	Standard operating procedures and nonstandard situations	Class scheduling procedure	C3I & nuclear strategy; models and test procedures air pollution	Increase repertoire of SOPS
Bureaucratic interests and politics Wilson, Allison	Organizational interest in wealth and power	Housing vs. Deans MIT & PU re alumni fund raising	Patriot, C31, BMDO, EPA	Establish competition across bureaucracies

Source: Professor Kenneth A. Oye, 17.950 Science, Technology, and Public Policy, Cambridge, MA. M.I.T. Fall 2001

In addressing the need to take into account social considerations, Kelvin Willoughby suggests:

- There is frequently a range of alternative technological means available which are suitable for the attainment of primary objectives within a given field;
- The number of alternatives in the range may be increased over time by conscious human effort;
- Alternative technological means of similar suitability, for the attainment of certain primary objectives, may vary widely in their suitability for the attainment of secondary objectives;

The informed selection of technological means, taking into account secondary objectives as well as primary objectives, combined with long term efforts to expand the range of available alternatives, is an important element of social, economic, and environmental policy. (Willoughby 1990)

One of the few people to focus on technology choice, not from an engineering or economic perspective, but from a social perspective, was E.F. Schumacher (Schumacher 1973). Although an economist, Schumacher focused not on economic optimality, but rather on forms of development he believed would optimize the needs of the people in poor and rural regions of developing countries. He believed that technology was at the cornerstone to achieving this goal. Schumacher's definition of "suitable technology" for "enlightened development" – low capital costs, low economies of scale, low skill requirements, and maximum use of local resources with minimum harmful local impact – has infiltrated much of modern practice. It's implementation, however, often overlooks both Schumacher's social emphasis as well as the assumptions necessary to reach his conclusions. Schumacher's conclusions are based on assuming an isolated region. Uniquely, Schumacher also believes in employment as an end in and of itself. He argues for the gradual evolution of a region: placing the needs and capacities of people over the production of goods, integrating the development of rural areas rather than promoting Westernized industries in metropolitan areas, considering meta-economic factors as a pre-condition of analysis, and emphasizing self-reliance at all levels of society.

Schumacher's work focuses on optimizing the interests of the individual. This focus, and much of his conclusions, fit in with basic development theories. The interests of the individual, however, are inherently intertwined with the interests both of the nation in which that individual is resident, as well as of companies within (and outside) that nation. Two alternative development theories exist which take a different approach to this intersection of interests. Catch-up theories focus on developing nations catching up to developed nations through technology transfer. Once caught up, the developing nations then seek out a niche in either the global or local market (Evans 1979) (Westphal 1985). Leap-frog theories recommend developing countries finding a competitive space in the market from the start, and to then make use then of that advantage (Brezis 1991) (Nonaka 2001) (Weiss 1989). In contrast to Schumacher's focus on optimizing the interests of the individual, the focus of both catch up and leapfrogging theories is the interests and advancement of the nation. The cross-demographical impact of national advancement is in turn a function of the advancement itself and the further policies of the nation.

The work which follows quantitatively looks at cost structure and qualitatively looks at economic and political climates in two case countries to observe the competing roles these factors can play on the feasibility of manufacturing and marketing an upcoming technology in a given region. The influence of regional factor inputs is incorporated into the modeling of costs and manufacturing systems. The ideal manufacturing decisions according to cost, are contrasted with what is actually happening within each country to gain insights on the impact of factors not related to production costs. Given this increased understanding of the dynamic factors driving technology decisions, a discussion ensues of whether the current decisions are the most "appropriate" technology decisions, and if not, what would be. "Appropriate" technology for the company well-being, versus individual well-being, versus national well-being, are seen as being intertwined, sometimes coinciding, and sometimes conflicting. Cost analyses from the study are used to aid this discussion. Lastly, given the discussion of "appropriate" technology, measures are suggested for policy intervention to move towards such technology choices. Equity, fairness, preservation of culture and society, and human and environmental rights are all considered important aspects of social well-being, and relevant to different degrees for policy intervention (Oye 2001) in the producing nation and region.

2. Problem Statement

Mixed forces have led to different levels of research and development in and of application of structural composites in vehicle bodies in the United States versus China.

- What are the forces currently leading to the given levels of R&D in and application of structural composites in each country?
- How do changes in cost structure due to new vehicle innovations, such as the recent Automotive Composites Consortium's composite unibody body-in-white design, weigh in comparison to other political and economic forces in affecting the feasibility of the vehicle in each country?
- How do differences in regional cost-input factors weigh in affecting the cost structure of composite production, and hence its feasibility in each country?
- Are current drivers in each country leading to economically and socially optimal outcomes, or is there a need for government intervention?

3. Background: The Rise of Structural Composites

3.1. Structural Composites in Automotive Vehicle Bodies: A Technical Perspective

Composites are made from two or more distinct materials. Combining two or more materials into a composite can improve properties (such as strength, toughness, and/or durability) over the original material. The word "composites" in engineering contexts typically refers to the fiber-reinforced metal, polymer, and ceramic materials originally developed for aerospace use in the 1950s (UDel 2001) In this work, however, the term "composites" refers only to the subset of composites with a polymeric matrix, and not to those with rubber, metal, or ceramic matrices.

Fiber-reinforced polymers or fiber-reinforced plastics (FRPs) are combinations of fibers and/or particulate fillers in a polymeric matrix (Owen 2000). The reinforcement functions to carry load or to control strain. The matrix is a bonding medium. It transfers load, and provides continuity and structural integrity. Common fibers include glass, carbon (graphite) or aramid, although fibers may also be of natural, polymeric, metallic or ceramic origin. Common fillers are of mineral origin such as chalk (calcium carbonate) or alumina trihydrate. Ground minerals, powdered metals, and pigments are also used as fillers. Polymer matrices fall into two main classes, thermosets and thermoplastics. Thermosets are liquid mixtures of chemical constituents. They react with the reinforcement to form a solid matrix. This solid matrix can only be further shaped through machining. Thermoplastics can be softened or re-melted by heat, thus permitting some reshaping with a method other then machining (Owen 2000).

Carbon composite material properties are compared with the material properties of the two other body-in-white materials modeled in this study – glass composite and steel – below in Table 3.

Table 3: Material properties comparison for carbon composites, glass composites, and steel

Material	Tensile Strength (Gpa)	Tensile Modulus (GPa)	Specific Strength (Gpa)	Specific Modulus (GPa)
Carbon	3.5	230.0	2.00	131.4
E Glass	3.4	22.0	1.31	8.46
Steel	1.3	210.0	0.17	26.7

The unique properties of composites lead to both advantages and disadvantages over the current standard automotive body material, steel. Advantages include the following:

1) Superior strength and stiffness to weight ratios, allowing composite parts to be lighter than a comparable steel part while offering similar mechanical properties. An all-carbon-composite vehicle body is estimated to be 55% lighter than the equivalent body made out of steel.
2) Increased NVH (noise, vibration, harshness) performance through significantly higher dampening performance, while maintaining the necessary performance in stiffness
3) Improved fatigue resistance, causing the durability of load bearing mechanisms to be increased.
4) Customizable physical properties according to the expected load characteristics of the application.
5) Unique energy absorption mechanisms through matrix microcracking and viscoelastic properties of the matrix which, given proper design, can lead to greater crashworthiness
6) Superior resistance to a wide range of chemical attack and an inability to oxidize (rust). Although polymer resin has high chemical resistance, reinforcement does not, so it is

important to manufacture the vehicle such that the polymer resin or a coating is used to act as a barrier to these agents.

7) Inherent design flexibility allowing the consolidation of multiple steel pieces into a single composite part (thereby leading to lower tooling and assembly costs), and allowing more radical or aerodynamic shapes to be produced. (Kang 1998).

Disadvantages include low modulus compared with steel and aluminum, the cost of developing design methods and obtaining design data, the need to develop and invest in new fabrication and production techniques, and the cost and lead-time to develop successful products (Owen 2000). Production-related disadvantages include achieving 2mm tolerances and Class A surface quality. Advantages and disadvantages, as they relate to the market in each country, are discussed further in Section 3.3.

3.2. Structural Composites in Automotive Vehicle Bodies: Current Application

3.2.1. The Extent of Application of Structural Composites in the U.S.

The use of polymers in U.S. automotive applications has risen from an average of approximately 60 pounds per vehicle in 1970 to more than 360 pounds in 1999 (APC 2001).[1] Lower-performance commodity polymers, such as SMC and random-glass RTM, by 1998 made up 7.5% of the mass of a typical vehicle. They have found their way into sportside truck models in fascia, fenders, and trims, and heavy truck applications as cab steps, bumpers, spoilers, doors, fenders, toolbox doors, and even full cabs (Kobe 1999). Passenger vehicles incorporating

1 This estimate varies by source. The 1999 Ward's Automotive Yearbook shows 168 pounds of plastic and plastic composite material in the average family vehicle produced in 1977 versus 245 pounds in the average family vehicles produced in 1999.

composite body panels have included GM's Saturn, EV1, Corvette, Firebird, and Camaro, as well as Ford's Tarus/Sable, Mustang, and Windstar (Kobe 1999). Advanced composite applications in vehicle bodies have been far less extensive. The two most well-known advanced composite applications have been the GM 800 truckbox and the GM 805 tailgate, both of which were structural reaction injection molded. On the horizon sit many prototypes – Jeep's Commander, Lotus's answers to Porsche's Boxster and Porsche's Elise, Honda's hybrid SUV, DaimlerChrysler's ESX-3, and VW's "One-Liter Car" – sporting advanced composite bodies (RMI 2002).

3.2.2. The Extent of Application of Structural Composites in the P.R.C.

A different set of drivers seem to be affecting the application of composites in China, and possibly, across emerging market nations. In 1997, Daimler Chrysler unveiled a $6000 price tag, molded-composite 4-seat compact car – not for the European or American market, but specifically for manufacture and sale in China (RMI 2002). In 1999 when the rest of the world was still pumping out vehicles made over 75% out of metal and with conventional drive trains, Huatong Motors was producing out of Sichuan Province the world's first commercial-volume vehicle that features a composite/plastic chassis, a composite/plastic body, and hybrid electric drive (Reed 1998). Other automotive manufacturers are following DC's and Huatong's lead. Composite Automobile Research Ltd. of California recently expanded its Californian research operations to a new center in Beijing (Deloitte&Touche 2000). Its wholly owned subsidiary, World Transport Authority Inc., offers a multi-purpose vehicle made out of a combination of fiber-glass composite and steel specifically for manufacturing and sale in developing countries

(WTA 1999). These vehicles are already produced in Columbia and the Phillipines. As of May 2001, a site license was achieved to begin producing these vehicles in China (WTA 1999).

3.3. Structural Composites in Automotive Vehicle Bodies: Current Issues

3.3.1. Current Issues in Automotive Composites Application in the U.S.

Political debates in the U.S., and, generally, in developed nations, on the automotive application of composites circle around three points: environmental benefits, safety concerns, and consequences for corporate and national competitiveness.

Composites provide one of the best-known technical solutions to reducing vehicle weight and decreasing aerodynamic drag. These qualities make up two of the five key developments set out by PNGV as the primary route to achieving necessary polluting emission reductions: (1) Weight reduction through substitution of lighter materials, especially in the body of the vehicle, to reduce fuel consumption and thereby emissions; (2) reduction in aerodynamic drag to reduce fuel consumption and thereby emissions; (3) reduction in tire rolling resistance through new tire designs with higher pressures, new structures and new materials; (4) a variety of improved and alternative powertrains and powertrain/drivetrain combinations; and (5) improved end of pipe emissions through improved catalytic converters. By reducing vehicle weight and improving aerodynamics, not only do composite vehicle body components reduce emissions ((1) and(2)), they also increase a manufacturer's options to incorporate (5), low- or zero-emission drive trains (which have not achieved the power of conventional drive trains).

The use of polymers, for autobody components brings up two issues for safety: the performance of composites and the performance of light-weighted vehicles in crashes. The properties of a reinforced polymer composite are not necessarily uniform throughout the material. A composite with uni-axial alignment of fibers will be strongest, stiffest, and toughest in the direction of the fibers, and weakest perpendicular to the fiber direction. A composite with multi-axial alignment of the fiber reinforcement, has uniform strength, but the magnitude of that strength is not as great as can be achieved with uni-axial or partial fiber alignment. To ensure desired properties during crash scenarios would either require understanding and being able to design the polymer properties to the forces which would be experienced, or knowing that the properties of the uniform multi-axial alternative were sufficient. Given the auto industry's lack of experience with composite BIW designs, reliable computer crash simulations are lacking. Particularly uncertain is the response of composite components at joins. In composites' favor is that in comparison to steel and aluminum, composites' thermal expansion is indeterminably small, meaning that composite components are less likely to change their shape with temperature, and thus less likely to disrupt other parts in the system causing those parts to fail. (Chawla 1987).

The second safety issue in applying composites to automotive applications is whether the light weighting which improves environmental performance would lead to less driver and passenger safety during collisions. In the case of a crash with a heavier vehicle, the lighter vehicle will receive more of the force of the joint impact. The result for driver and passenger safety, and the amount of design compensation which might be necessary, thereby depends significantly on the weight of the other vehicles on the road (or allowed on the road.) On the other hand, a composite vehicle in a crash with a stationary object, should actually experience less force, and thus display better crash properties than a heavier vehicle traveling at the same speed at the time of the crash. Although more than 70% of all crashes annually involve multiple vehicles, over 56% of all fatal crashes involve a single vehicle hitting a stationary object (NHTSA 2001). Such data suggests that the light weighting of vehicles could actually play a pivotal role in reducing fatalities, especially if regulation placing over-arching weight limits on on-road vehicles were also enacted.

From a cost perspective, it is unclear if the consolidation of parts allowed by composites will lead to lower overall production costs, and for what production volumes. The fewer tools required in component production and the fewer parts to assemble could lower costs. Higher production material prices (the composites), larger tool sizes, higher join material prices (the adhesives), and automated assembly requirements could raise costs.

From a demand perspective, the low surface quality of composites compared to metal is considered by auto manufacturers to be less favorable on the market. Costly surface treatments are often required to allow for painting, additional paint layers are used to compensate for the composite surface, and even then the surface quality of the final product does not match what can be achieved on a metal body. On the other hand, the increased design flexibility allowed by composites could increase demand for a given vehicle.

3.3.2. Current Issues in Automotive Composites Application in the P.R.C.

The environmental and safety implications of composite automotive BIWs discussed in section 3.3.1 for the U.S. are equally relevant for the P.R.C. Differences in vehicle driving patterns, powertrain efficiency, and fuel type in China may, however, lead to differences in the impact of BIW material changes on emissions. Likewise, the cost and demand factors influencing the manufacturing costs and marketability of composites are significantly different in China than the U.S. From a cost perspective, composite component production is generally considered to have higher labor requirements and lower initial investment requirements than steel. They are also generally considered to have overall lower component production costs at production volumes under around 70,000 annually. These assumptions are looked at in this work. Little is known about the labor requirements for and the overall cost structure of composite assembly. These assembly factors are also addressed.

The demands of emerging markets potentially are more favorable for composites than demands in developed nations. World Transport Authority, Inc., an automotive technology company which focuses on enabling developing countries to domestically produce a rugged, inexpensive, utility vehicle for domestic use, outlines four unique needs in their target markets: (1) being able to cross streams and traverse deep rutted, rocky uneven dirt paths, (2) being easy to privately maintain and repair, (3) adaptability to different situations, including being able to carry loads up to 1250 lbs, and (4) being capable of burning several types of fuel, depending on what's available. (WTA 1999). Composites' advantages over steel in corrosion-resistance and durability, are well-suited to these needs. GM market analysis has shown vehicle surface quality to hold less influence on demand in developing nations (Berger 2002). The difficulties of achieving a Class A surface with composites is thereby less of an issue. Likewise, costly, structurally unnecessary, paint layers can be excluded. Safety of and public perception of the safety of composite vehicles, a large concern in the U.S., may not be equally in the forefront in China. Lower levels of education and less developed private litigation channels may enable lower safety standards to be accepted.

3.4. Structural Composites in Automotive Vehicle Bodies: The Stakes

3.4.1. Current State in the U.S. of Relevant Issues

Air pollution caused by automobiles currently constitutes 60% of all air pollution in the US and 80% of air pollution in US urban areas (Percival 1992). This air pollution has been estimated by the Department of Transportation to cost US society between $30 billion and $349 billion in social costs (Economist 1996). In addition to their role in air pollution, motor vehicles account, primarily through gasoline consumption, for about a third of global oil use, and 53% of the oil use in the United States (MacKenzie 2000). Given estimates of recoverable oil and plausible assumptions of moderate growth in demand, world oil product can be expected to begin its decline within the next 7 to 10 years (MacKenzie 2000). Under current conditions, all of these numbers are getting worse. A rise in the number of motor vehicle miles traveled, an aging of motor vehicles on the road due to longer vehicle retention rates, and a rise in the total number of motor vehicles have offset the reductions achieved so far through emissions standards (Anderson 1999). The environment provides a classic example of an interest the market would systematically under support due to externalities, as well as of an interest, which according to organization theory, would be systematically under-represented and under-addressed.

In the year 2000, the total economic cost of motor vehicle crashes in the United States was $230.6 billion. This represents the present value of lifetime economic costs for 41,821 fatalities, 5.3 million non-fatal injuries, and 28 million damaged vehicles. The cost components include productivity losses, property damage, medical costs, rehabilitation costs, travel delay, legal and court costs, emergency services (such as medical, police, and fire services), insurance administration costs, and the costs to employers. Values for more intangible consequences such as physical pain or lost quality of life are not included in the estimate (NHTSA 2000). The effect further light weighting of vehicles could have on these deaths, injuries, and social costs is uncertain. A 1991 NHTSA study estimated that the reduction of the average weight of passenger cars from a previous 3700 pounds to 2700 pounds has increased fatalities by 2000 and serious injuries by 20,000 annually. (NHTSA 1997). A 1997 NHTSA report estimated that a 100-pound reduction in average vehicle weight would lead to 302 more fatalities and 1823 more serious or moderate injuries per year. (NHTSA 1997). Vehicles such as the Smart Car show that design can enable safety in small, lightweight vehicles. The Smart Car's crashworthiness results are among the best on the market, despite it weighing nearly half the curb weight of an average vehicle (Smart 2002).

The competitiveness of the Big Three, potentially closely linked to their choices in product and process design, is no small matter for the U.S. people or for the U.S. economy. New-vehicle sales equal 20% of total retail in US, or $646.8 billion. GM and Ford each employ over 400,000 people world-wide, with over 70% of those employees in the U.S. Over 1 million people are employed in the sale of new vehicles. Extrapolating from the fact that 560,000 people in the US receive health care through Ford alone, more than 1.5 million U.S. citizens have their health care made possible under the umbrella of the Big Three. (GeneralMotors 2001) (Ford 2001) (DaimlerChrysler 2001)

3.4.2. Current State in the P.R.C. of Automotive Composite Application Relevant Issues

Beijing, a city of over 11 million people, yearly ranks first or second in the World Bank's "Ten Most Polluted Cities in the World" (World Bank China-Beijing Environment Project II). Shanghai experienced its first actinic phenomena, a chemical reaction stimulated by sunlight on air pollutants that increases the threat of pollutants, in 1995. Chongqing, Chengdu, and Guangzhou have also witnessed actinic phenomena (UNCHINA 2000). According to SSTC's report on Sustainable Development and China's Agenda 21, the air quality in more than 500 major Chinese cities is below WHO criteria (UNCHINA 2000). By the year 2020, it is predicted that 42 percent of China's population, more than 600 million people, will live in urban areas (WRI 1999). Air and water pollution already are estimated to cost China 8% of its GNP, around US$54 billion. Environmental factors have been identified by the Chinese government as one of the four leading influences on the morbidity and mortality of China's people today. (WRI 1999).

The air pollution in China is yearly getting worse. As of 1998, the single largest source of air polluting emissions in China was coal combustion in industrial boilers (WRI 1999). If no significant control measures are taken, automobile emissions will surpass industrial emissions and become the primary source of air pollution in the coming years (UNCHINA 2000). In Guangzhou, auto emissions have already become the number one source of urban air pollution (UNCHINA 2000). Not only growing fleet size is leading to more air pollution. Increased vehicles on the roads are leading to lower highway travel speeds. At these lower speeds engines run less efficiently, emitting more pollutants. Vehicles in developing countries also have longer lifetimes. Although less-polluting vehicles may be added to the fleet, older highly polluting models are continually repaired rather than retired. As of 1998 there was one farm vehicle for every 100 residents in rural areas and one auto for every 400 residents in urban areas (Xing 1998). Automobile ownership, excluding farm vehicles, reached an estimated 21.7 million by the end of 2000 (UNCHINA 2000).

Demand for automobiles in China is rising. The number of privately owned automobiles in China increased on average by 27 percent annually between 1988 and 1998. The vast majority of these vehicles are trucks, buses, and cargo vans (again, farm vehicles are not included in this category). Experts believe that demand for inexpensive farm vehicles – in the form of trucks, pick-ups, vans, and sedans – reached 3.5 million units a year by the turn of the century and will rise to 5.5 million by 2010. The onslaught of demand for a family car in China is estimated to set in around 2005, when the average per capital annual household income should reach RMB 60,000 ($7230). As the market grows, China's farm vehicles and passenger-car industries are destined eventually to merge into a single motor-vehicle industry. (Xing 1998). Registered motor vehicles in China (excluding scooters) are expected to reach 44 to 50 million by the year 2010. By then, annual vehicle production is expected to reach six million (WRI 1999).

Regardless of these environmental concerns and social costs, it is not surprising that economic development continues to be the number one priority in China at all levels of society. Per capita, China continues to be one of the world's poorest countries (WRI 1999). Thirty percent of the Chinese population falls below the U.N. poverty line. A report based on Chinese National

Bureau of Statistics household data found that a quarter of the rural population was below the minimum level of daily caloric intake. The U.N., in surveying six poor counties, found over one third of the people had a per capita income below the national poverty line. (China's national definition of "poverty" places more people above the line than poverty as defined by the U.N., and is estimated by the U.N. to approximate the number of people under necessary daily caloric intake.) Nor does everyone live long enough to be classified as "in poverty." On average nationally, the infant mortality rate is 50/1000, and in remote poor areas it exceeds 100/1000. (UNCHINA 2001). The automobile industry has been identified through the State Council's automotive industrial policy (AIP) since 1994 as one of the "pillar industries" towards guaranteeing economic advancement (Xing 1998) If producing more automobiles is seen as leading to fewer starving people, it is easy to understand how the environmental implications of those vehicles could be far from a Chinese priority.

3.5. Structural Composites in Automotive Vehicle Bodies: Current Regulation

3.5.1. Regulatory Environment Surrounding Current Issues in Automotive Composites Application in the U.S.

Several U.S. legislative and regulative initiatives address consumption of scarce gasoline resources, decreasing air polluting automobile emissions, and improving automobile occupant safety in the U.S. Each of these areas will be discussed in turn below.

Title 49. Transportation Chapter 329 of the US Code deals with the issue of fuel consumption by automobiles (USCodeT49:Ch329). These provisions were first created through the Energy Policy and Conservation Act of 1975 under what came to be known as the CAFE (Corporate Average Fuel Economy) Standards. There is currently a freeze prohibiting the use of authorized funds to carry out any sort of rulemaking that would alter the CAFE standard, including studying whether SUVs should meet more stringent standards. The standard thus continues to be at its 1985 level of 27.5 mpg for passenger automobiles, and 20.7 mpg for light trucks (Bamberger 2001).

Alternative fuels are addressed both under CAFÉ as well as under several sections of Title 42. The Public Health and Welfare . Title 42 addresses assessment of alternative policy mechanisms for addressing greenhouse gas emissions (Sec 6375), electric motor vehicles and associated equipment research and development (Sec 13384), establishment and use of life cycle analysis methods and procedures (Sec 8254), and regional petroleum reserve accounting (6237). These sections within Title 42 are policy discussions and recommendations, and are not directly associated with standards or regulations. (USCodeT42).

Emission controls for motor vehicles date from the 1965 Motor Vehicle Air Pollution Act, as amended by the 1967 Air Quality Act. The legislation today most directly addressing the issues of air pollution through new stringent motor vehicle emissions controls is the 1970 Clean Air Act (USCodeT42). The regulations concentrate on reductions in emissions most responsible for ozone and particulate matter pollution, including nitrogen oxides and non-methane organic gases. The Clean Air Act generally prohibits states and localities from adopting or enforcing motor vehicle emission control standards. California, due to its history of leading the country in air pollution problems and stringent standards combined with its unique problems as a result of its climate and topography, induced Congress to allow it to apply to waive the preemption of state emission control standards. California's low-emission vehicle (LEV) and clean fuel (CF) requirements went into effect in 1991. The LEV program required the phasing in of four classes of light and medium duty vehicles over the next decade: (1) Transitional Low-Emission Vehicles (TLEVs), (2) Low-Emission Vehicles (LEVs), (3) Ultra-Low-Emission Vehicles (ULEVs), and (4) Zero-Emission Vehicles (ZEVs). The emission standards for CO, NOx, and formaldehyde are progressively more stringent in each class. (Anderson 1999).

The Federal Motor Vehicle Safety Standards and Regulations, issued by the National Highway Traffic Safety Administration under Title 49. Transportation, Section 301, and common law product liability are the two main areas of law which protect the safety of automobile occupants. The Federal safety standards are regulations written in terms of minimum safety performance requirements. These requirements are to be such "that the public is protected against unreasonable risk of crashes occurring as a result of the design, construction, or performance of motor vehicles and is also protected against unreasonable risk of death or injury in the event crashes do occur" (USCodeT49:Ch301). Most of these crash avoidance standards are specific requirements on different automobile parts, for example to help reduce the likelihood of break failure or to ensure a specific decency of windshield de-fogging. This is different than in Europe, where crashworthiness standards state that an automobile must be able to protect a driver from any injuries at particular speeds when hit in each of the possible directions, and that an automobile must be able to protect a driver from serious injuries and death at other higher speeds specific to different possible directions of impact.

3.5.2. Regulatory Environment Surrounding Current Issues in Automotive Composites Application in the P.R.C

Since the promulgation of the Environmental Protection Law in 1979, the first of its kind in China, 5 pollution-control statutes and 10 natural resource conservation statutes have been enacted. Both China and the U.S. have signed the 1997 Kyoto Protocol, though neither country has ratified the Protocol. Both countries are Parties to the 1992 United Nations Framework Convention on Climate Change. (WRI 1999). None of the current Chinese regulatory efforts are directed towards the light weighting of vehicles. The development of natural gases as an environmentally sustainable alternative to coal and leaded gas has begun in some Chinese cities; however, it is far from becoming widespread as of yet. In the Ninth Five Year Plan, China has stipulated its aim to produce 30,000 natural gas powered automobiles by the year 2000 and 200,000 by the year 2005. The plan expects to reduce sulfur dioxide emissions to 21 million tons and save 1.5 million tons of gasoline. More studies to formulate effective and appropriate regulations to ensure compliance, however, are still needed. (UNCHINA 2001).

China's tariffs on automobiles stand at 80-100%, depending on the category of the vehicle. Tariffs on auto parts are at 23%. There are tight restrictions on the distribution of automobiles and parts, strict local content requirements, and multinationals are required to participate in joint ventures. As a condition to establishing a joint venture, there are mandatory technology transfer requirements (Nolan 2001). There is also a $30,000 investment cap (Economist 2002), although compliance with the investment cap can potentially be easily circumvented (Steinfeld 2002). The regulatory environment in China, however, is quickly changing. China has agreed that by the year 2006, tariffs on automobiles will have fallen to 25%. Tariffs on auto parts will fall to 10%. China has agreed that former tight restrictions on distribution of automobiles and parts within China will be eliminated three years after accession to the WTO, and all local content rules will also be eliminated. Multinationals will no longer be required to participate in joint ventures, or to transfer technology (Nolan 2001). The previous $30,000 investment cap is to be raised to $150,000 (Economist 2002).

3.6. Structural Composites in Automotive Vehicle Bodies: The Stakeholders

A large factor in technical choice is what technologies even come into consideration. The factors that influence what comes into the engineer's design frame, the manager's perception of market need that it passes down to the engineer, or the government regulation that changing market incentives for firms and their engineers result from stakeholder and interest group dynamics at firm, regional, and national levels. Stakeholder interests in the U.S. versus in China are discussed below.

3.6.1. Stakeholders in Automotive Application of Structural Composites in the U.S.

The General Motors, Daimler Chrysler, Ford three-company dominance in the U.S. auto industry lends towards oligopoly market failures[2] and makes Stiglerian[3] regulatory capture. In the interest of maximizing short-term profits as well as return on investment on sunk costs, the U.S. auto

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[2] American antitrust policy has swung back and forth over the past century between favoring concentration and favoring deconcentration of industry. Concerntrationalists believe that strong innovation capacity is dependent on monopolistic firms with extensive resources to put towards R&D. Deconcentrationalists argue that large firms with overwhelming market share lose the inventive to innovate and will abuse their market power rather than looking to better serve the needs of the market. (Hart 2000).

3 Stigler, in his "The Theory of Economic Regulation," defends the thesis that as a rule, regulation is acquired by the industry, and is designed and operated primarily for its benefit. He argues that an industry tends to seek one of four main policies from the state: (1) direct subsidy of money, (2) control over entry by new rivals or protective tariffs, (3) suppression of substitutes and complements, and (4) price fixing. (Stigler 1971).

manufacturers would tend to resist non-incremental change in technology. Although some work on composites is being done, and a minimal level of structural composites have been implemented, they are generally considered not feasible on a large scale, given cost versus demand dynamics in the market. The U.S. auto industry tends to resist environment-oriented change, which so long as demand for environmentally-friendly characteristics is lacking in the market, would increase costs without a feasible increase in prices. Driver safety, which holds weight in the market, carries more weight in technical decisions. Also concerned about vehicle light weighting initiatives is the steel lobby, who fear losing market standing to lighter weight, alternative BIW materials such as composites and aluminum.

Several forces, however, act in favor of speeding environmental progress and light weighting initiatives. The first is the global nature of environmental problems, both the resulting international environmental movements and regulations, and the variation across markets internationally. In nations such as Europe and Japan, the Big Three must compete in more stringent regulatory environments. They also must compete in the U.S. market more fuel economic and environmentally friendly vehicles from these same nations. There are also multiple small groups whose interest would be served by developments towards a more environmentally friendly vehicle. Stakeholders such as the plastics industry, alternative powertrain developers and producers, and environmental advocacy groups, are forces that could potentially be strengthened and joined. The plastics industry continues to be primarily comprised of small "mom-and-pop" shops producing resins as well as parts. Exceptions include Owens Corning and 3M in glass fiber production, and Budd and Meridian in part production. The American Plastics Council (APC), comprised of more than 80% of the U.S. monomer and polymer production and distribution capacity works to promote the benefits of plastics and the plastics industry. APC has government affairs representatives at the federal, state, and local levels to deliver resource conservation and plastic benefits messages to legislators and local audiences, and to advance legislation beneficial to the plastics industry. APC recently opened the Automotive Learning Center in Troy, MI (APC 2001). Also formed was, in 1988, the Automotive Composites Consortium, a collaboration of the U.S. auto manufacturers. Its mission is to "conduct joint research programs on structural polymer composites in pre-competitive areas that leverage existing resources and enhance competitiveness" (ACC 1996-2002). Competition between the composites and aluminum industry to fill the demand for lightweight vehicle body materials, has led to conflict between rather than banding together of the two.

A final factor influencing technology choices, and at the forefront of government and industry discussions is the general public. Polymer composites are publicly perceived as being less safe both due to people's concept of "plastic," as well as due to the concern over plastic vehicles being lighter weight, and therefore more easily crushed or thrown around. The environmental benefits to be gained from lower air pollution and less oil consumption are diffuse interests. Personal safety in a vehicle, on the other hand, is a much more concentrated interest. Following Oelsen's theories of organization, the public will fail to create the dynamics in which composites will be considered as a technology option, even if the individual environmental benefits outweighed the individual costs.[4] There is also a general perception that "plastics" are less environmentally friendly due to recyclability limits. Lifecycle studies suggest that the environmental benefits of the emissions reductions through light weighting would significantly outweigh the negative environmental effects of a body material being ill-suited for recycling (Han 1994). The validity of these studies could be questioned depending on the maintainability of composite bodies, and the value placed on energy savings versus other environmental factors.

3.6.2. Stakeholders in Automotive Application of Structural Composites in the P.R.C.

Given the nature of China's "market economy with Chinese characteristics", the incentives structure, stakeholders, and inter-stakeholder dynamics are not the same as in the U.S. Local environmental agencies, the National Environmental Protection Agency, other national ministries, and the local governing body are all involved in environmental law making. The incentive structures, and the resultant interests of these bodies are quite complex. A local governing body may, in addition to creating legislation, own and run an automobile component or assembly plant. A local EPA may, in addition to passing and enforcing environmental legislation, own a tail-pipe emissions cleaning device manufacturer. A national government agency could, in addition to its regulatory responsibilities, own an aircraft industry manufacturer and thereby have interest in expanding composite production. This crossing of interests requires extensive research to understand incentive structures, beyond what will be possible in this work, whose focus is on the implications of different cost structures between the U.S. and China. A general look at some of the dynamics observed is provided in 3.7.2. It is hoped that anticipated in-country research shortly after the publication of this thesis may provide more insights into the stakeholder dynamics within and between local and national government agencies as well the different automotive and supplier firms. An important group of stakeholders in the Chinese auto

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[4] Oelsen argues in his "Rise and Decline of Nations: Summary of the Logic of Collective Action" that concentrated interests will tend to be overrepresented and diffuse interests

industry in addition to government agencies are the foreign joint venture investors. These foreign firm interests could include market access, cost savings for export production, and greenfield opportunities for technology experimentation.

3.7. Structural Composites in Automotive Vehicle Bodies: Recent Case Insights on the Current Political Dynamics

3.7.1. Recent Case Insights on the Political Dynamics in the U.S. on Automotive Composite Application

Several examples exist suggesting that the Big Three have had success in achieving regulatory capture in the U.S. The CAFE provisions were relaxed by the National Highway Traffic Safety Administration (NHTSA) for model years 1986-1989 from 27.5 to 26.5mpg in response to petitions from manufacturers facing stiff penalties for noncompliance. Attempts to raise or change the CAFÉ standards have proved too controversial for passage. A freeze has been put in place prohibiting the use of authorized funds to carry out any sort of rulemaking that would alter the CAFÉ standard, including studying whether SUVs should meet more stringent standards. The current standard continues to be 27.5mpg for passenger automobiles and 20.7mpg for light trucks. (Anderson 1999). By 1994, the corporate stance on reducing greenhouse gas emissions continued to be that the government should avoid any temptation to adopt mandatory requirements. Along with the Big Three were the oil and steel lobbies. Doyle writes, "Mobile was, in fact, one of the most consistently shrill voices in the engineering controversy surrounding electric vehicles, both nationally and in California." As the Kyoto summit approached in 1997, the automakers were still holding the same stance. They claimed the treaty would be bad for the United States in terms of jobs and the economic vitality of the country. Clinton's proposal ended

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underrepresented in a society comprised of ration individuals (Olson 1982).

up calling for an aggressive program of incentives and tax breaks to encourage business to cut their emissions, but no standards. (Doyle 2000).

Within the U.S., the plastics industry, alternative powertrain developers and producers, and environmental advocacy groups, form an alternative force impacting government and public decisions. CARB, an electric-vehicle battery producer, issued a report in 1995 demonstrating the near-term feasibility of electric vehicles. Ovonic, who works on electric vehicle batteries, moved to advertise the extent of its battery progress, although some claim airing of the ad was blocked by GM. The Rocky Mountain Institute identified composites in vehicle applications as key to protection of the environment. When in June 1995 new public opinion polling sponsored by the California Manufactuing Association found that Californias didn't want electric vehicles, CALSTART, the NRDC, and the Coalition for Clean Air published a reply arguing that "the poll asked … misleading, negative questions using discredited information to achieve the result." In early 1996, not long after the rollback of California's EV mandate, the Sierra Club Legal Defense Fund (SCLDF) in San Francisco, petitioned the US Justice Department (DOJ) alleging a conspiracy among the Big Three automobile producers to stifle the development of electric vehicles. In June 1997, a group of five environmental and public health organizations – the Union of Concerned Scientists, ALA, NRDC, ACEEE, and the Environmental and Energy Study Institute wrote to President Al Gore voicing their concern about PNGV's lack of attention to improving air quality and warning against using the partnership as the government's sole approach to improving fuel economy.

The American auto industry generally lobbies against technology-forcing legislation, claiming that being forced to meet those requirements would "kill the auto industry" (Doyle 2000). These instincts, typically of incumbent industries, may hurt the Big Three. It is difficult to predict what first-mover advantages, if any, companies focusing on innovating to meet or even anticipate regulation may gain. Foreign competition has precident for gaining first-mover advantages over the Big Three – the Swedes and Germans in safety, and the Japanese in quality, fuel economy, and emissions control. With another oil shock hitting the U.S. economy in January 1979, Americans were clamoring for more efficient automobiles, but Detroit couldn't provide them. Consumers turned in droves to Japanese models. Chrysler was hit the hardest. By December 1979, Chrysler convinced Congress to save it with a $1.5 billion dollar bailout. Additional help for all of the auto manufacturers ranged from high-level U.S. jawboning to slow down Japanese exports to special "regulatory reform" packages designed to ease up on the beleaguered auto industry (Doyle 2000). "'Big Three executives spent most of the [Tokyo 1997] auto show's press preview pleading for more time and resources to find practical and more affordable solutions to global warming,' reported Dave Phillips of the Detroit News (Doyle 2000) (Phillips 1997). Meanwhile, by 1997, Toyota had the world's first "hybrid," the Prius. Half gasoline half electric powered automobile, the Prius had 66mpg fuel economy, half the carbon dioxide production and 90 percent less hydrocarbons and NOx of a conventional car. Shortly thereafter, Honda announced that it would introduce in late 1999 the first hybrid vehicle for sale in the United States, the Insight, receiving 61mpg city and 70mpg highway. In December 1999, GM announced that it would buy low emission V-6 engines and transmissions from Honda as part of a "worldwide partnership," whose immediate effect was helping GM meet California's emission standards, and GM hooked up with Toyota, as well for help with Prius technology (Doyle 2000).

Doyle writes, “Honda is not a member of the auto industry’s newest power circle – the “Global Six” – comprised of Ford, GM, Toyota, Volkswagen, DaimlerChrysler, and Renault-Nissan . . . . But Honda is more profitable per vehicle than any one of the Big Six . . . .” Honda’s R&D budget ($3.2 billion) is about one-third of GM’s ($9 billion), but has arguably done more with it” (Doyle 2000). Maryann Keller, in a July 1999 Business Week article, observing Honda’s success and asked if Honda could continue to “go it alone”, responded ‘There’s absolutely no proof that monstrous size conveys competitive advantage” (Doyle 2000) (ThortonBusinessWeek 1999).

3.7.2. Recent Case Insights on the Political Dynamics in the P.R.C. on Automotive Composite Application

Despite the complex system of legislative and policy tools in place and the network of environmental officials throughout China, compliance with environmental regulations remains low, essentially because economic development remains the country’s priority at all levels of society. Insufficient investment has also prevented realization of these goals. WRI discusses advances in the current regulatory climate:

> As part of its effort to strengthen environmental law enforcement, the government revised its criminal code to punish violations against the environment and resources. This step may provide law enforcement agencies with some power. However, the vagueness of standards in many laws and regulations, coupled with the lack of a comprehensive enforcement regime, has led to a situation where many environmental laws still reflect deals cut between the local environmental protection agencies, NEPA, other ministries, local government bodies, and the polluting enterprises. Thus, the degree of actual

compliance and enforcement depends on the region concerned and the personalities involved. Often, the richer the potential investor, the more strictly environmental policy will be applied (People'sDaily 1997) (WRI 1999).

For the next decade or so, China's rapid development will likely lead to further uncertainty in the regulatory regime. In the meantime, an increasing array of resources are being devoted to enforcement, and discussions are currently underway to elevate NEPA to ministerial status, which may give NEPA more leverage and authority in law enforcement. Nonetheless, many Chinese officials adamantly hold that economic development must come before environmental protection. They also disagree about how stringent environmental initiatives need to be to protect the health of billions of citizens while maintaining economic growth. This internal struggle enhances the paradoxical quality of Chinese environmental law, which may at once appear both simple and complex, or lenient and severe (Ferris 1997) (WRI 1999).

Of equal concern to the environment in policy literature, and speaking also to the Chinese economic development priority, has been the indication that dynamic forces may be at work in local economies which prevent technologies "tailored to fit the psychosocial and biophysical context prevailing in a particular location and period"[5] from being chosen, and where the

[5] This description is Kelvin W. Willoughby's definition of "appropriate technology" laid out in his book, *Technology Choice: A Critique of the Appropriate Technology Movement*, published in 1990. The term appropriate technology was common to an entire social movement and branch of academic literature in the '70s and '80s. It has been used variously to refer to particular philosophical approaches to technology (Drengson 1982), to ideologies (Morrison 1978), to political-economic crtique (Lodwick and Morrison 1982), to social movements (Winner 1979), to economic development strategies (Robinson 1979, Diwan and Livingstone 1979), to particular

technologies chosen actually constrain economic development (Willoughby 1990). Small scale production, using a relatively larger number of workers and less capital, has been shown to have more favorable production costs (indicating higher efficiency) as well as higher return on investment (than larger scale production) for developing countries (Stewart 1990). Studies pointed out that not only were small-scale and appropriate technologies neglected in developing country regions, but also that the environment affecting choice of technology was usually hostile to them and systematically biased to favor the choice of large-scale capital-intensive technologies (Stewart 1990). This hostile-to-appropriate-technology environment stems from multiple sources. One such source is the currently fashionable focus on export-oriented policies (Stewart 1990). Stewart Thomas and deWilde further describe the problem:

> Even when macro-policies are intended to stimulate the use of appropriate technology, inappropriate technology is invariably selected . . . . Very little difference [was found] between a freer market-oriented capitalistic system and a more centrally planned socialistic development model. The choice of technology is strongly influenced by the investors. In this case, foreign donors appear to be instrumental in the promotion of capital-intensive technologies. Bureaucracies and political systems find it difficult to cope with labor-intensive appropriate technology solutions because the results are only apparent in the long term; the project are less spectacular; and the government bureaucrat does not occupy as significant a position. (Stewart 1990).

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types of technical hardware (Canadian… 1976, Darrow Keller and Pam 1976, Magee 1978), or even to anti-technology activities (OTA 1981). (Willoughby 1990).

The case of composites in vehicle bodies in China, however, may be contrary to this theory. As described at the beginning of this section, composite vehicles are finding a unique niche in developing countries, and especially in China. Production of vehicle body components, at least, are believed to require high labor, low capital investment, and lead to more environmentally friendly vehicles due to their light-weighting properties.

There are many possible explanations for this push towards China with automotive composites.

Theory 1: Composites Come Out Cheaper.

Given China's unique set of factor inputs, composites may be a cheaper vehicle body alternative than steel in developing countries, or at least in China. Production of composite components is more labor intensive than steel, taking advantage of China's lower wages. Raw materials, if sourced internally, could be cheaper.[6] The delta between Chinese and US material supply quality and the delta between Chinese vs. US material supply costs for composites versus steel, will be important in weighing the cost implications of choosing the one over the other. Composites components are known for having lower unit costs than steel at low production volumes, due to the lower capital investment required. To date, annual production volumes of China-based plants continue to be mostly under 70,000, which is the cross-over point below which estimates to-date have found composites to be less expensive than steel (Kang 1998).

[6] Protective tariffs can cause local material prices to be higher, despite lower quality. This statement assumes that following full entrance into the WTO, local materials will find price in accordance with their quality and subsequent worth in the global market.

Although several factors can be expected to increase production costs in a developing country such as China, such as higher expatriate salaries, higher reject and scrap rates, and increased downtimes, these can be expected to be the same for both composites and steel. The requirements for composite assembly, however, point less towards them having developing country advantages. Increased labor usage over automation is a commonly cited reason for moving the assembly of vehicles, if nothing else, to developing countries. Composites, through part consolidation, actually save on the amount and costs of assembly, in comparison to steel. Further, due to the delicate nature of adhesives, automation is often highly recommended, if not required to acquire the necessary bond between components. Thus, assembly of composite vehicle bodies at minimum do not take particular advantage of developing country resources, and may even be ill-suited for such environments. The cost-advantages of composites at low production volumes, although well-suited to the current production environment in China, are no longer the obvious choice when the rapid expansion of the market for new vehicles in China is considered.

Theory 2: Market Demand in China is Less Antagonistic to Composites

As discussed in section 3.3.1, China, as a developing nation, may have a set of unique transportation needs not usually found in the U.S. Composites do not have the rust and corrosion problems of metals, and when structurally designed correctly, they can be more durable. Their durability can be beneficial on the varied road conditions. Their corrosion resistance becomes key in lasting through the longer vehicle lives experienced. Composites may not fair as well in the need for easy private maintenance and repair. Although a composite body would have fewer overall pieces, the repairability of composite body panels and adhesive joints requires further technical development. Potential exists for snap-and-fit joints as well as for body panels deformations to be popped back into shape, but these options may not achieve necessary structural integrity. Adhesive joints may also have easy repair options, but supply of repair adhesive would have to be such that it could be privately purchased. The difficulties of achieving a Class A surface with composites repeatedly faced for industrialized nation markets, is not an issue in developing nations, according to market analyses showing the Chinese to be less concerned with shiny surfaced vehicles (Berger 2002). Finally, public perception of composites would likely have less sway in China, or composites may not have the poor safety image, which has developed in the U.S., in China at all.

Theory 3: Greenfield Investment Opportunities Provide an Opportunity to Try New Technologies

China and other developing nations, not only provide growing markets to tap, but also greenfield investment opportunities. These greenfields can act as a playing field for new technologies to multinational giants who in their home countries are held to the status quo by high sunk costs. In such cases, international forces can be driving the technology, such as the international drivers for more environmentally sound private transportation and thus vehicle light weighting, and the region, in this case China, is merely decided on as the optimal testing ground.

Although the greenfield nature of China's investment opportunities may be one factor leading to it being chosen as the testing ground, it will be difficult to isolate as the main cause. According to early location and place theories, markets, sources of supply, and transportation costs are three main factors in a firm's decision on where to locate its production facilities. These factors must be balanced against cost reduction opportunities through economies of scale (see early location and central place theories: (Weber 1909) (Christaller 1933) (Loesch 1940) (Heilbrun 1981) (Krugman 1995)). Information networks, tacit knowledge held by the region, and other less tangible factors, as discussed further under the Theory 4, can also be key resources drawing a firm to a location.

Theory 4: National Policy and National Factors are Pulling Composite Technology

There are many reasons why China as a nation might act or want to be acting to develop specialty in the production of composite vehicles.

With certain technologies, the most frequently cited being the aircraft industry, substantial learning and scale effects make entry into the industry difficult. Further, it has been found in cases such as civil aviation that substantial spillover benefits from the civil aircraft firms are derived by the nations holding these firms, and that these benefits do not tend to diffuse readily across international borders. (Busch 1988). Automobiles may similarly have national border limited spillovers.[7] Spillovers specific to composites range from aircraft and military implications, to bathtubs and other household items, to bridge supports and building technologies. Although simpler composite component applications have been shown in the United States to be produced at the mom-and-pop level, more sophisticated structural applications are done by larger firms, in conjunction with automotive and aerospace firms farther

[7] The tendency for countries to develop domestic automobile companies (France, Germany, Italy, Japan, China, Malaysia) could be supporting evidence of the auto industry's similarity to the aircraft industry, although this phenomenon could also be being driven by other factors.

downstream in the supply chain, and large chemical companies farther upstream in the supply chain.

Regional or national specialization in a technology or industry has other draws. As originally pushed by Alfred Marshall, clustering of producers in a particular location yields advantages including, not only lower transportation costs, but also lower transaction costs and other economies of scale benefits (Marshall 1890). Following cumulative causation theories, the more firms that locate in a region, the more will want to locate in the region, and the more it will be cost-effective to replace imports with local production (Krugman 1995) (Pred 1966). This circular reinforcement through increasing local external economies of aggregation, is admittedly tempered by local external diseconomies of aggregation such as congestion and higher land costs (Krugman 1995) (VonThuenen 1960). Despite admitting the existence of diseconomies of aggregation, the benefits of agglomeration economies and industrial clusters are currently subscribed to by both firms and nations in the world-wide economy. Michael Porter goes so far as to promote his cluster theory over, or at minimum in addition to, industrial policy (Porter 2001).

Porter defines clusters as geographic concentrations of interconnected companies, specialized supplier, and service providers; firms in related industries; and associated institutions (for example universities, standards agencies, and trade associations) in particular fields that compete but also cooperate. Porter writes, "A cluster is much more than an economic organization facilitation production efficiency. The essence of a cluster lies in the exchange of insights, knowledge, and technology, and in offering a structure that offers the incentives and flexibility to innovate . . . Location within a cluster facilitates continuous improvement, encourages strategic differentiation, and creates pressures for innovation." (Porter 2001). The importance of firms' ability to develop knowledge links to their subsidiaries, suppliers, and customers is further defended by Johansson (Johannson 1991). The key role of network innovators, on the other hand, is defended in greater depth by DeBresson (DeBresson 1991). Storper and Walker's work, looking at how such clusters evolve, also points overwhelmingly at the importance of the skills developed by a cluster or region. Although at first, with an entirely new technology, a firm can locate anywhere with equal opportunity, as a firm grows, the advantage of it's location increases. Compensatory advantages of amassing large quantities of labor, machinery, materials, and structures in a limited area, and internal economies of a large integrated workplace and reduced transaction costs create a barrier to locational freedom. Productivity increases brought by development within the region of norms, culture, and consciousness around the experience of work also act as a disincentive for the firm to relocate. (Storper&Walker 1989). The same forces that keep a firm in a particular region as it grows, draw other firms to a region which has developed itself as the headquarters for a particular technology.

Potential incentives for China to have national policy directed at creating national or regional specialization in automotive composite vehicle body production seem many. There could be possible spin-off advantages both for technological and, thereby, economic advancement, but also with military and national security implications. The location and cluster theories discussed above suggest that regional specialization would have cumulative advantages, attracting even more firms and causing even greater knowledge build-up and specialization in the region. As the technology region continued to grow, tacit knowledge would be developed only known in that region, and giving firms the additional incentive of choosing to produce there, so as not to have to learn and re-develop that tacit knowledge somewhere else. A region with such specialized knowledge would, if these theories hold, also become the more likely place for the next generation of composite vehicle-body technology to be developed and first manufactured, as it emerged. With the increasing likelihood that composites auto bodies will be the norm in industrialized nation vehicles within the next 10 to 30 years, as environmental concerns become more and more of an issue, creating a regional or national specialization in composites ahead of the rest of the world could be an extremely smart tactical move by China.

Key to understanding the drivers behind, the political feasibility of future development in, and the social and nation implications of China either choosing or being chosen for such composite specialization will be understanding who the stakeholders are in the choice of composite versus steel body production in China. State-owned enterprises, and hence certain well-established sectors of the government, for example, are the cornerstone of the steel industry in China. Who holds the stakes in composite production, and what are those stakeholders position, politically, compared to the steel industry? How many jobs does each side hold, and what would be the social and geographic implications of one growing over the other?

4. Methods

4.1. Technical Cost Modeling

Technical cost modeling was developed as a method for analyzing the economics of alternative manufacturing processes without the prohibitive economic burden of trial and error innovation (Busch 1988). Its application has been extended to analyzing the implications of manipulating design specifications or process operating conditions on production costs within a given manufacturing process as well as across alternative manufacturing processes (Kirchain 2000). In the same way that present-day mathematical models allow designers and manufacturing engineers to understand the physical consequences of their technical choices before those choices are put into action, technical cost models harness the engineering approaches at work within these physical models to avoid expensive strategic errors in product development and deployment (Kirchain 2000).

Although cost may appear a simple quantity to measure, traditional economic and accounting tools fail when attempting to relate specific technical choices and changes to their economic implications. Classical economic analyses see cost as a summation of factor inputs. For example, Pindike and Rubinfeld in their basic book, *Microeconomics*, teach "to select inputs to produce a given output at minimum cost" by finding the derivative of a total cost equation such as $C=wL+rK$ (Pindyck 2000). Here w is wage rate, L is hours of work per year, r = Depreciation Cost + Interest Rate, and K is hours of use of machinery per year. To include material in such an approach, the equation might instead read as follows: $C= wL+rK+aM$, where "a" is material price and M is quantity of material required per year. These equations do not account for the fact that cost is a function of the entire manufacturing system – changes in design parameters, process parameters, or material choices do not have isolated consequences, rather ripple effects throughout the manufacturing system. When substituting materials within an existing process, the cost change cannot be measured alone in the differences between the new and old material prices. The new material changes yield, operating rates, tooling lives, and more. Accounting tools are also limited, in that they must be based on experience from the performance of existing facilities and designs. In process-based cost models basic scientific and engineering principles from thermodynamics, physics, etc. are used to extrapolate the consequence of technical choices on key associated process parameters, and thus on cost.

A process-based cost model, like any other engineering process model, serves as a mathematical transformation, mapping a description of a process and its operating conditions to measures of process performance; in this case, cost (Kirchain 2000). The technical cost model is constructed through three steps: (i) identifying relevant cost elements, (ii) establishing contributing factors, and (iii) correlating process operations to cost of factor use. (Kirchain 2000). Identifying relevant cost elements defines the scope of the model. The relevance of any particular cost element is a function of both the process under consideration and the question the model is to address. For example, while transportation cost may not be a direct consequence of a plastics-forming technology, it may be pertinent if one is comparing the cost of producing plastic parts versus analogous, but heavier, metal parts. On the other hand, logistics may play a role in comparing processes which have different batch-production characteristics. In comparing the competitiveness of composite monocoque production in the U.S. versus China, it was important to identify which factors would differ between the two countries, as further discussed in 4.2.

Once the model's scope has been defined the details of the manufacturing process can be mapped to their contributing factors (Kirchain 2000). For the SRIM model, the preform tool, the preform cycle time, the molding tool, and the molding cycle time were identified as elements whose requirements would change with design parameters, and could be predicted based on the initial parameters describing the part. This mapping to design parameters was achieved in one of two ways – based on existing empirical evidence or according to basic scientific and engineering principles. A more detailed discussion of the calculation of each of these variables can be found in Section 4.4.1.

The third step in creating a technical cost model is translating the process factors into per piece, annual, and investment costs. Cost elements can be grouped into two categories: variable costs and fixed costs. Variable costs are directly associated with a unit of output. Their magnitude (on a per period basis) increases linearly with the total number of units produced. Fixed costs fall into one of two groups: one-time capital expenditures and recurring payments only weakly related to the quantity of parts produced. (Kirchain 2000). In the SRIM model, the variable costs include material, direct labor, and energy. The fixed costs are equipment costs, tooling costs, building costs, maintenance, and overhead labor. Material cost is a function of the price of the raw material, the design of the component, the yield associated with the process, and trim scrap. Direct labor cost is a function of wages paid (including all costs to the manufacturer of employing a worker), the number of laborers necessary to run the process, and the paid operating time. Energy costs are a function of the prevailing energy price, gross operating time, and a regression of listed consumption requirements of the processing equipment versus equipment size.

One-time expenditures under the model's fixed costs are annualized by using the capital recovery factor, CRF = $[r(1+r)^m]/[(1+r)^m-1]$, to capture its associated opportunity cost. Here *m* is the number of periods over which the cost is allocated, and *r* is the percent discount rate representing the time value of tying up assets in this capital. Notably, the relevant number of periods, m, may be different for each of the elements of cost even for the same process, since different equipment will have different lifetimes, as will different tools, as will the cost of building space. Equipment costs include both relationships between equipment size and costs, as well as the ability to compute how many pieces of equipment working in parallel would be required to produce a specified number of parts in the required time period. Whether or not the equipment would be dedicated is also taken into account. Tooling costs are most often determined using empirical data to relate prices paid for previous tools to parameters describing the components they produce, such as dimension, shape, and material properties. Building costs are simply calculated based on the prices per square meter of building space and creating a relationship between space requirement, equipment size parameters, and conventional practices (material handling requirements, safety specifications, etc.). Finally, overhead labor (supervisors, janitors, etc) can be estimated by applying a burden rate to the direct labor requirement. This simplistic treatment of overhead is considered acceptable when the goal is to analyze the relative costs of technical changes in part or process. (Kirchain 2000).

There are three final considerations which are key to incorporate into a technical cost model: intensity of production, time, and material flows. Two types of production volumes are distinguished – net production volume (PV), the demanded output of the facility, and gross production volume (GPV), the total units which must be produced to meet that demand. (GPV takes into account that each machine will produce a certain percentage of defective parts which will have to be thrown out.) While GPV is used to determine total cost per period, unit cost is determined by dividing the total cost by the net PV. A final production-related parameter is the net facility capacity, which allows the model to investigate how steeply costs will climb if an operation is not fully utilized. Operating time is key to production cost. Operating time is broken into available operating time, paid operating time, and required productive operating time. The available operating time does not include planned unpaid downtime, planned paid downtime, or unplanned downtime. Required productive operating time represents the total amount of time needed to produce the gross number of pieces demanded. The most difficult part of determining the required productive operating time, is machine cycle times. Cycle times affect the number of parallel streams necessary to achieve a specified production volume, as well as variable costs such as labor and energy. Part design and process operating conditions affect the magnitude of the cycle time. The relationship between part design, process operating conditions, and cycle time, are found by combining both theoretical and statistical (econometric regression analysis) methods. Finally, it is important to track material flows to determine both the intensity of production at each process step as well as how much the material and waste costs. (Kirchain 2000).

4.2. Regional Factors in TCM

In identifying relevant cost elements to compare the cost-structure and feasibility of composites in the U.S. versus the P.R.C., a set of factors were sought which would lead production costs for the identical technologies to differ across two regions. Each factor was associated with the set of

Table 4: Regionally Dependent Factor Inputs Affecting Technical Cost Model Variables

Constraint	**Affected Model Variables**
Labor	
Wage	**Wage*
Skill	**Downtimes, *yields, *scrap, cycle time (break down into intrinsic versus total)*
Experience	*Initial investment, labor availability*
Absenteeism	*Fixed versus variable labor costs, "buffer labor" factor → number of laborers * (1-absentee rate)*
Raw Materials	
Price	*Price breakdown → actual price, cost of transport, tariffs/fees*
Quality	*Yes/no meets specs, yield and scrap hits for yes's, line rate, design change requirements (thicker, etc.)*
Reliability	*Inventory, back-up supplier, yield losses (due to expiration)*
Electricity	
Price	**Price per kWhr*
Reliability/availability	**Downtime, capital (industrial boiler, etc.)*
Real Estate	
Price	**Price per sq. m*
Components (Source)	
Imported from supplier	*Transportation cost*
Imported from OEM's production facilities	*Transportation cost*
Produced by local firm w/ OEM oversight	*Transportation cost, investment for oversight functions, yield, scrap, line rate, product and process design changes*
Produced locally by OEM	*Transportation cost, investment for oversight functions, yield, scrap, line rate, product and process design changes*
Capital (Source)	
Discount rate	**Discount rate*
Imported from supplier	*Transportation costs*
Produced by local firm w/ OEM oversight	*Transportation costs, investment for oversight functions, yield, scrap, downtime, product and process design changes*
National Policies (Tariffs, procurement, local content or technology transfer incentives/requirements, plant subsidies, hi-tech or FDI tax credits, R&D subsidies or tax credits, in-country R&D center incentives/requirements)	*Each policy can be defined as affecting a set of the above-described variables.*

model process variables which would be affected by changes in that factor. This mapping can be seen in Table 4.

To pursue country differences for all of the factors listed in Table 4 as well as to extract the quantitative impact on the associated model variables for each factor was beyond the scope and time constraints of this thesis. Instead of pursuing links between factor inputs and model variables, given limited time, direct data was sought on a subset of model variables, estimated based on the above mapping to be most significant in manufacturing cost differences between the two countries. Data was gathered from companies in each country on these factors through a survey (See Appendix 1). Some additional overarching questions were included to add insight on driving forces in each country. The results of the survey were incorporated into the model as country differences in direct wages, capital recovery rate, installation costs, price of building space, building recovery life, working days per year, average downtime, reject rates, scrap rates, machine costs, raw material costs, and tool costs (see Table 5). In Table 5, R_i, S_i, K_i, M_i, and T_i, are the average reject rate, scrap rate, machine costs, raw material costs, and tool costs, respectively. The "i" represents the step of the component production or the station number in assembly. The steps of glass- or composite-reinforced composite component production are (1) preforming, (2) preform trimming, (3) injection molding, and (4) final trimming. The steps of steel stamping component production are (1) blanking, (2) blank trimming, (3) stamping, and (4) final trimming. The number of stations in assembly varies with production volume.

Table 5: General Inputs for U.S. versus P.R.C. SRIM, Stamping, and Assembly Models

Variable	**U.S.**	**PRC: Now**	**PRC: +20 yrs, Conservative**	**PRC: +20yrs, Optimistic**
Exogenous Cost Factors:				
Direct Wages	\$20.00/hr	**\$1.50/hr**	**\$1.50/hr**	**\$1.50/hr**
Capital Recovery Rate	12%	**18%**	**17%**	**16%**
Capital Recovery Life	15 yrs	15 yrs	15yrs	15yrs
Electricity Price	\$0.07 /KWhr	\$0.07 /KWhr	\$0.07 /KWhr	\$0.07 /KWhr
Aux. Equipment Cost	20%	20%	20%	20%
Installation Cost	15%	10%	10%	10%
Overhead Burden	35%	35%	35%	35%
Maintenance Cost	10%	10%	10%	10%
Price of Building Space	\$1080 /m^2	\$150 /m^2	\$150 /m^2	\$150 /m^2
Building Recovery Life	20 yrs composite 40 yrs steel 40 yrs assembly	**10 yrs** composite **25 yrs** steel **25 yrs** assembly	**10 yrs** composite **25 yrs** steel **25 yrs** assembly	**10 yrs** composite **25 yrs** steel **25 yrs** assembly
Other:				
Working days per year	240	251	251	251
Working hours per day	20	20	20	20
Average Downtime	20%	**50%**	**40%**	**30%**
Reject Rate	R_i	**103%R_i**	**103% R_i**	**103% R_i**
Scrap Rate	S_i	**101%S_i**	**101% S_i**	**101% S_i**
Machine Costs	K_i	**117.5%K_i**	**117.5% K_i**	**110% K_i**
Raw Material Costs	M_i	**112.5%M_i**	**100% M_i**	**87.5% M_i**
Tool Costs	T_i	**50%T_i**	**50% T_i**	**50% T_i**
Utilization	100%	**50%**	**70%**	**90%**

National policies are not incorporated into the model as direct factors affecting production costs, but are instead considered external influences, which act to change the parameters of the system. National policies such as tariffs, subsidies, tax incentives, intellectual property rights, local content requirements, and in-country R&D requirements have direct financial consequences, which if known, are easy to record in the model, and to observe their impact on overall manufacturing costs. Direct consequences of national policies aimed at improving education and training, or increasing worker mobility are more difficult to incorporate into the model. Potentially affected variables would include labor, scrap rates, reject rates, and downtimes. Procurement affects demand, not cost. National policies aimed at increasing knowledge networks and technology transfer, are even harder to quantitatively assign direct model variable impacts. The focus here is only on two policy areas: (1) given current cost structures for the application of composites, what policies in each country would affect those cost structures to create a more desirable incentive structure, and (2) given current stakeholder dynamics, what policies and policy-making methods could be used to encourage more desirable technology outcomes.

It is hoped that by better understanding the role of cost versus other factors, such as market demand and stakeholder interests, in driving technical choices, more appropriate policy actions can be taken.

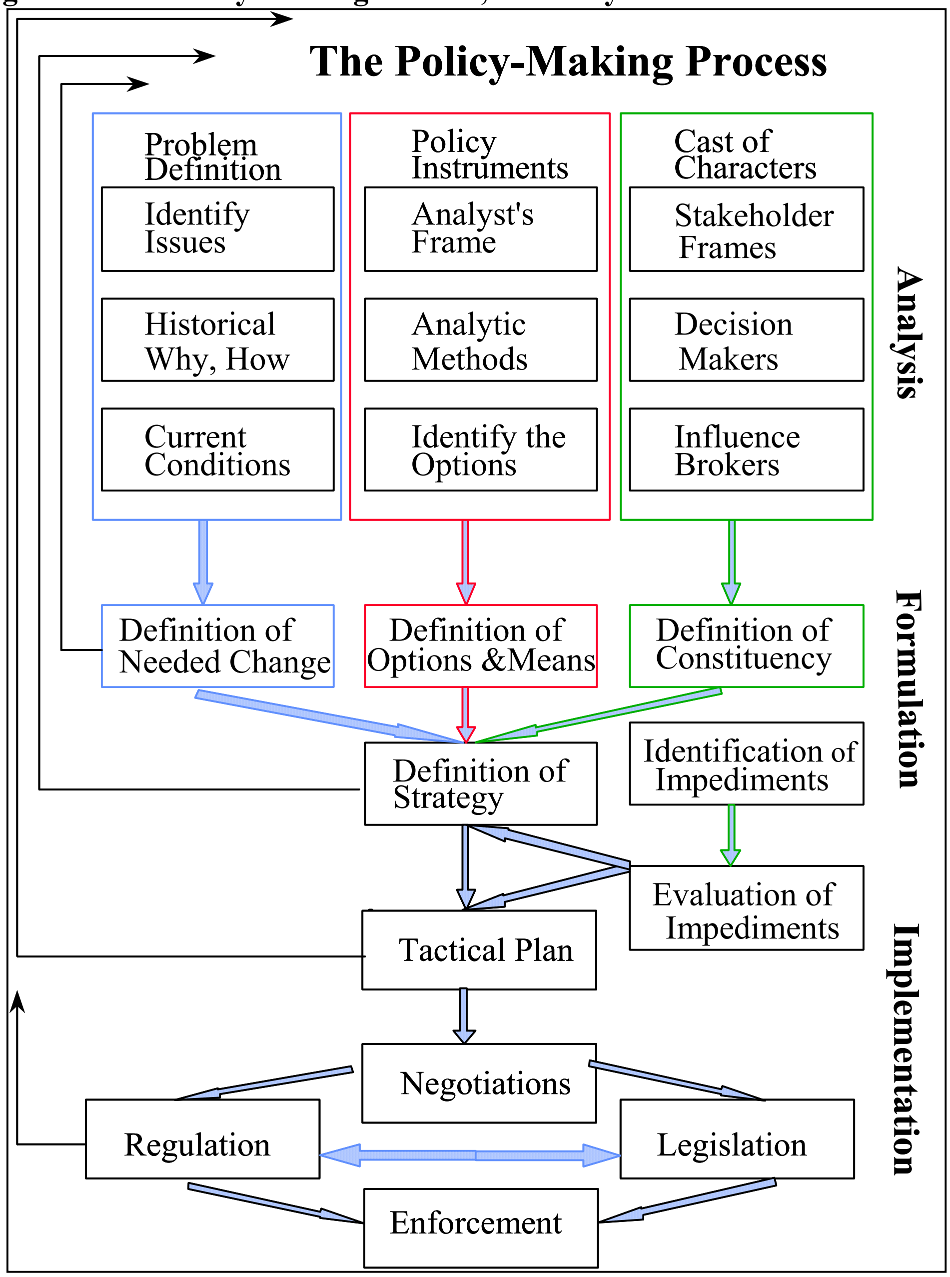
4.3. Policy-Analysis Methods

Policy intervention is a tool for addressing market or institutional failures to drive technology choices towards collective social goals. Equity, fairness, preservation of culture and society, and human and environmental rights are all important aspects of social well-being, and defined here as relevant to policy intervention. (Oye 2001). Although policy can affect product cost structures or limit options or feasibility for a firm, as discussed in 4.2, these cost factors may or may not be most influential in the firm's technology choice. Within the defined framework, uncertainties exist both regarding costs and demands. Decisions are made with imperfect information. Short-term outcomes may weigh more in decision-makers' choices than long-term ones. Firms can be risk-averse. Actors can be resistant to new technologies or change. Concentrated interests of individuals, such as job-retention, can have greater significance in decisions than success of the firm. Concentrated interest of the firm can have greater significance in decisions than the diffuse and less tangible significance of social health and well-being.

The creation of policy requires understanding such issues and related interest groups so that solutions can be engineered to harness individual interests, group interests, and market forces. Multiple guides to the policy-making process have been published to guide the policy-maker through this process (Walker&Fisher 1994) (Weinmer 1999) (Tabors 2000). The Policy Making Process set out by Richard Tabors and shown in Figure 3 is used here (Sussman 2001). Six policy-making steps from Tabor's chart receive particular focus: definition of the problem, identification of the issues, understanding of current conditions, identification of the cast of characters, definition of needed change, and discussion of options and means to achieve needed change. The development of each of these steps makes up the chapters of this thesis. Problem definition, according to Tabor's The Policy-Making Process, occurs in Chapter 2. *Issues* associated with the choice of composites versus steel in each country are *identified* in Section 3.3. *Current conditions* are laid out concerning the application of composites in Section 3.2; current conditions concerning the environment and social welfare are described in Section 3.4; and current conditions concerning regulation are detailed in Section 3.5. The *cast of characters*, or stakeholders, are defined in Section 3.6, and brought to life in Section 3.7. Chapter 7 discusses Tabor's *needed change* is defined by addressing how "appropriate" technology differs when considering the company, versus the nation, versus the individual. Different *options and means* for implementation are discussed depending on the unit of focus – firm, nation, or individual, and in the case of China, on the development theory believed. The discussions of

Chapter 7 are based on the insights shed in Chapters 5 and 6 on the role of cost in regional differences in choices. Some additional insights are also gained on non-cost drivers through the second half of the survey sent out (See Appendix 1), as also presented in Chapters 5 and 6.

Figure 3: The Policy-Making Process, Courtesy of Richard Tabors



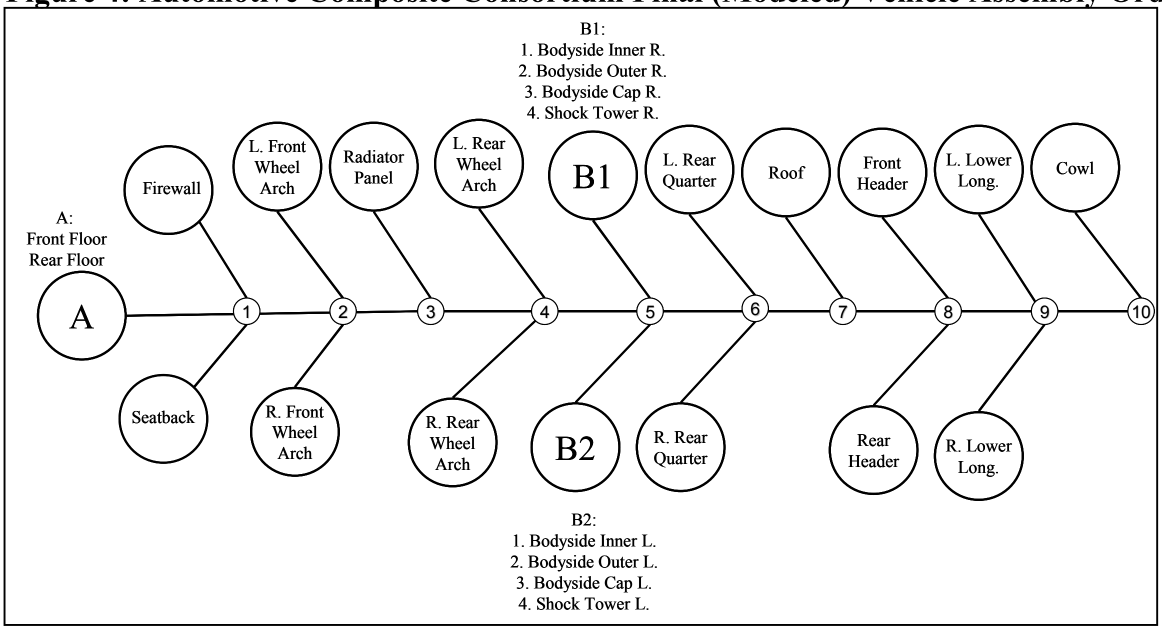
4.4. Production of a Composite Body-In-White

4.4.1. The Case Vehicle

Design and processing information for the composite case vehicle was drawn from the Automotive Composite Consortium's (ACC) Focal Project III. The ACC was formed in August 1988 to conduct joint research programs on structural polymer composites in pre-competitive areas that leverage existing resources and enhance competitiveness. It is a collaborative effort between Ford, GM, and Daimler Chrysler. The case vehicle chosen for this study is the result of the ACC's Focal Project III. The design goal of the Focal Project III was to produce a body-in-white with minimum mass, which maintained structural integrity and cost-competitiveness at medium to high production volumes (20,000-250,000 body units per year).

The Focal Project III vehicle is a JA model a four door mid-sized sedan. The sedan has a 108" wheelbase, is 186" long, 71"wide, and 54" high. It consists of 25 components and 37 inserts. The components are 60wt% Bayer AG's 2-component polyurethane, Baydur 420, and 40% carbon fiber reinforcement. The inserts are mild steel. All of the components are produced according to the SRIM (structural reaction injection molding) process. The preforms for the bodyside inners, outers, and caps, the floor pieces, the firewall, the seatback, the front and rear wheel arches, the radiator, the front and rear headers, the right and left lower longitudes and the cowl are created using P4 (programmable powder pre-form process). The preforms for the front floor, front lower longitude, rear floor, and roof use layered carbon-fiber fabric to create the preform. The assembly of the 25 components and 37 inserts is achieved by joining the parts with SIA Plastilock 731SI adhesive. To cure the adhesive, hot air impingement mechanisms are incorporated into the fixtures at 260°F for 180 seconds. The order of assembly is shown in Figure 4.

Figure 4: Automotive Composite Consortium Final (Modeled) Vehicle Assembly Order



4.4.2. The Two Comparitors

To develop a fuller picture of the competitiveness of composites in vehicle body-in-white applications, two additional cases were developed.

4.4.2.1. The Base Case

The base case, a steel comparitor, represents the typical vehicle currently on the market. This steel comparitor vehicle is what previous studies suggest would be the most cost-competitive steel alternative at mid to high annual production volumes (Kang 1998). It is based on the GM delta vehicle, is also a four-door mid-sized sedan. Delta vehicle has a 103" wheelbase, and is 185" long, 67" wide, and 57" high. The minor dimensional differences between the Delta and the JA vehicle, are for this comparison, insignificant. The delta vehicle is made up of 120 components and 130 inserts.

4.4.2.2. A Glass-Reinforced Body-In-White

The second comparitor is a glass-reinforced composite unibody. As shown in Table 3 in Chapter 3, carbon fiber's material properties allow significant weight reduction over glass fiber reinforced parts, and is as such an ideal choice for the Focal Project III's design goal of a minimum mass vehicle. With carbon fibers costing \$11.05/kg, this light-weighting has generally been assumed to come at a high, if not prohibitively high, cost. Although they create a lower strength material, and thereby require thicker part designs to maintain structural integrity, at only \$2.65/kg, glass fibers as reinforcement for the composite components provides an interesting comparison.

The glass-reinforced composite vehicle used the same general design as the carbon-reinforced ACC vehicle. For each of the 25 components, height and width were kept identical. To maintain structural integrity, the thickness of the components was increased. Stresses that result from bending are the most common form of loading that parts experience (Kang 1998). If the carbon-reinforced and glass-reinforced components are to exhibit the same stiffness, their deflection under the same loading force should be equal. The equation for deflection under bending loading is as follows:

$$\delta = \frac{FL^3}{3EI}, \quad \textit{where} \quad I = \frac{bh^3}{12} \quad \textit{such that} \quad \delta = \frac{4FL^3}{Ebh^3}$$

Here δ is deflection, F, loading force, L, length of the component, b, width of the component, h, thickness of the component, and E the tensile modulus of the component material. Setting deflection, loading force, length, and width equal for the carbon-reinforced and glass-reinforced components, results in the following:

$$h_g = \frac{1}{3}\sqrt{\frac{E_C}{E_G}}$$

Here, E_C is the modulus of the carbon-reinforced component, and E_G is the modulus of the glass-reinforced component. Each of these moduli, is a function of the volume fraction of resin versus reinforcement, and the moduli of the resin and reinforcement as follows:

$$E_C = V_c E_c + V_r E_r \quad \text{and} \quad E_G = V_g E_g + V_r E_r$$

where V_c is the volume fraction of carbon reinforcement E_c is the modulus of the carbon reinforcement, V_g is the volume fraction of the glass reinforcement, E_g is the modulus of the glass reinforcement, V_r is the volume fraction of the resin and E_r is the modulus of the resin. By definition, $V_c+V_r = V_g+V_r = 1$. In order to solve for E_G, a volume fraction had to be chosen for the reinforcement in the glass-reinforced components. It was decided to have $V_g = V_c$. The values for V_c, V_r, E_c, E_g, and E_r can be seen in table x below.

Table 6: Composite Components Composition and Tensile Moduli Breakdown

V_c (=V_g)	35.1	%
V_r	64.9	%
E_c	230	Gpa
E_g	72.4	Gpa
E_r	3.5	GPa

The increase in thickness of the glass-reinforced parts has ripple-effects throughout the SRIM process in material quantities, preform spray times, molding cycle times, and line requirements. Theoretically, the switch from carbon to glass may have additional process implications.

Differences in glass chemistry and conductivity ma lead to longer part and assembly cure times. Given a lack of empirical evidence substantiating this difference, however, it was not included in the current process model assumptions.

Assembly of the glass-reinforced components is modeled as being identical to the assembly of the carbon-fiber components. Due to their insulating qualities, two glass-fiber-reinforced composite components may actually require a longer adhesive cure time. The direct application of heat to the joint may also, however, make the difference in the thermal properties of the two composites inconsequential. Differences in adhesive cure times between glass-reinforced and carbon-reinforced components are therefore not incorporated into the model.

4.4.2.3. Alternatives Not Covered in the 3-Case Comparison

Several composite alternatives with potential for competitive advantage are not covered within the boundaries of the above study. The polyurethane resin chosen for the Focal Project III design is a thermosetting resin. An alternative to a thermoset resin is a thermoplastic compound. Although thermoset compounds exhibit superior thermal stability and lower water absorption, both extremely important properties in external body components, thermoplastics provide shorter cycle times, improved impact properties, and more studied recycling possibilities (Schuh 2000). On the down side, thermoplastics are less advantageous once the components reach the assembly stage, since thermosets require pre-treatment before bonding and even then acquire significantly lower joint strengths (Kinloch 1999).

A design alternative not addressed is composite panels on a structural steel space frame. Although a steel space frame has the advantage of allowing less plastic, and thereby lower overall component costs, there are fewer consolidation of parts advantages (and cost savings there from) in assembly.

Another interesting possibility for future study would be the cost-competitiveness of a Sheet Molding Processed (SMC) body-in-white. The advantages of producing the components by SMC would be significantly faster cycle times, fewer production steps, and lower material costs. SMC would, however, require thicker component designs, ribbing, and an increased number of overall components as compensation for the lower-performance level of the material.

Previous cost structure and feasibility evaluations on alternative composite component production processes can be found in "A Technical and Economic Analysis of Structural Composite Use in Automotive Body-In-White Applications" (Kang 1998). Kang looks at the cost-feasibility of production and assembly of a composite versus a steel body-in-white. Kang's thesis found, when comparing steel and composite BIW designs, the break-even point was 15,000 vehicles per year for Resin Transfer Molding (RTM) processed carbon-reinforced BIWs and 35,000 for RTM glass-reinforced and for SMC BIWs. He found composite materials, when broken into subsystems, to have no advantage in simple subsystems such as the roof. For parts requiring lay-up preforms, there are also disadvantageous where processing is such that cutouts can't be avoided, involving large material waste. A hypothetical hybrid BIW with a steel roof, SMC bodyside, and RTM glass-reinforced underbody and front end had a breakeven point between 50,000 and 75,000 vehicles per year (Kang 1998). Significant sophistication has been gained in the understanding of the design, processing, and assembly of composite vehicles since Kang's work. This progress is discussed in the development of this chapter. Its impact can be seen in the new results of this work.

Two other scenarios are not covered by this study and would be of interest for future work. The first is the competitiveness of the composite cases against other light-weighting body materials. The most common material other than composites competing against steel for a place in body components is aluminum. Aluminum may have the advantage against steel of lower investment costs, but the cost per kilogram of aluminum is much higher than steel. Where light-weighting has high utility, and steel is therefore not seen as an alternative, aluminum has the advantage over composites of being perceived as having lower technical risk. A second scenario warranting further study is the competitiveness at annual production volumes under 30,000. At these low production volumes, metal space-frame designs would become a competitor against the alternatives in this study, as would RTM and other low tooling investment processes.

4.4.3. The Process: Structural Reaction Injection Molding

The SRIM process is modeled as a four-step process: (1) pre-form making, (2) pre-form trimming, (3) injection molding, and (4) part trimming and inspection.

4.4.3.1. Preforming

Pre-form making, shapes the reinforcement material into the form of the part. This shaping of the reinforcement material can be accomplished in one of two ways: through the spraying of fibers or through the cutting and layering of woven fiber fabric. The type of pre-form method most appropriate for each part is chosen by the design engineer, and indicated by the user for the model.

The first of the two possible methods, the “spray method”, creates the perform shape by spraying the fibers onto a screen in the shape of the part along with either a powder or string binder to hold the fibers together. The screen is held in a press. Once the spraying is completed, the press closes, and is held at 180F until the binder has solidified, and the pre-form can be removed. The model assumes that for lower production volumes, the manufacturing line would be built with a two-robot spray station, while for higher volume production runs, the manufacturing line would be built with a carousel spray station. While the two-robot spray system handles two molds at once, the carousel system can handle up to six. The cycle time is split into four stages: press opening, 5 seconds; spraying; pre-form curing, 2.5 minutes; and part unloading, 30 seconds. The spray time is a function of the amount of fiber (in weight) required for each pre-form and the chopper gun rate. The chopper gun rate is 1.6kg reinforcement per minute for carbon fiber and 2.29kg reinforcement per minute for glass fiber.

The cost of the screen for the spray system is based on a regression of varying screen costs tied to the weight and surface area of the part. For carbon this regression is as follows:

$$\boldsymbol{C_{screen,C} = 8000 * W_C + 5000 * SA_C + 73040},$$

where W_C is the weight of the carbon-reinforced part, and SAC is the surface area of the carbon reinforced part. For glass, this regression is

$$\boldsymbol{C_{screen,G} = 8000 * X * W_G + 5000 * SA_G + 73040},$$

with W_G the weight of the glass-reinforced part, and SAG the surface area of the glass-reinforced part. The additional multiplier, X, is required due to the differences in density of the glass-reinforced versus carbon-reinforced parts.

$$X = \frac{\rho_C}{\rho_G} \cdot \sqrt[3]{\frac{E_C}{E_G}}$$

Component densities are calculated as follows:

$$\rho_C = V_c \rho_c + V_r \rho_r \quad \textit{and} \quad \rho_G = V_g \rho_g + V_r \rho_r ,$$

whereby p_C is the density of the carbon-reinforced composite, p_c is the density of the carbon reinforcement, p_G is the density of the glass-reinforced composite, p_g is the density of the glass reinforcement, and pr is the density of the resin. The densities of carbon reinforcement and glass reinforcement are given in Table 3 in Chapter 3.

The "lay-up method," uses fabric sheets of reinforcement. The fabric is pulled directly from the roll onto the forming machine, where it is cut prior to the required pattern. The cut patterns are then stacked two to five sheets thick directly on the SRIM press. To better form the stack of fabric sheets to the shape of the part, blocks in the reciprocal shape of the part, called conformers, are used to press the fabric into position. The number of fabric layers used depends on both the thickness and on the number of fiber orientations required to achieve the desired mechanical properties for the part. Vacuum pressure is used to pull the sheets (note, these sheets are dry fabric, not pre-pregs) into the shape of the mold. This entire process takes 2 ½ minutes to complete. Three-dimensional shaping of the pre-form occurs with the closing of the press during injection molding. The capital equipment expenditures and details for the Focal Project III design of the spray and lay-up pre-forming systems are shown below in Table 7.

Table 7: Alternate Pre-form Making Systems

	Spray System: Two-Robot	Spray System: Carousel	Lay-Up System
Equipment	$1.6M; two robots, two molds, automated robot inputs from cad, molds stationary, robot moves	$1.6M; robot, six molds, automated robot inputs from cad, automated shuttling	Cutting table (wheel cutter, computer, and vacuum system): $150K
Tools	$80K-$150K, $78K for i. & o. pillar	$80K-$150K	"Conformers": $500 ea., last 5000 cycles
Material	Carbon Fiber: $11.05/kg	Carbon Fiber: $11.05/kg	Hexcel Fabric (woven 24K): $6/lb
Labor	0, 1, or 2 workers depending on part size & on automation	0, 1, or 2 workers depending on part size & on automation	2 workers
Cycle Time	3min 5sec + (pre-form weight /chopper gun rate)	3min 5sec + (pre-form weight /chopper gun rate)	2 ½ min

4.4.3.2. Pre-form Trimming

During pre-form trimming, the edges of the shape are refined, removing any unwanted scrap. This "trimming" is estimated to remove 3% of the fiber originally sprayed and binded into form, and to require 90 seconds per part.

4.4.3.3. Injection Molding

During injection molding, between one and four resin dispensers, depending on the size and complexity of the part, inject the resin into the mold. A typical themoset resin for the reaction injection molding of structural automotive components is a two-component polyurethane. After the resin has been injected, the closing of the press forces the resin to infiltrate throughout the fibers of the pre-form. Depending on whether a powder or string binder is used, a 2.5 minute or 4 minute cure is then required, respectively.

Press costs for the injection molding set are estimated as a function of part length, part width, and the force required of the press. The regression used was developed by Paul Kang, and is independent of the component material (Kang 1998).

Kang's regression is as follows:

$$\textbf{\textit{Press Cost}} = \mathbf{49{,}400 + 590.0 * (\textit{Required\_Force}) + 94{,}000 * (\textit{Part\_Length} * \textit{Part\_Width})}$$

Kang's method for calculating required force is based on different assumptions than what is known about the process today. In Kang's calculations, it is assumed that the force to spread the resin throughout the mold is produced by the ejection force out of the nozzle. Instead using the closing of the press to infiltrate the pre-form with resin does result in some differences in fluid flow dynamics. Kang's initial force calculations are, however, kept for this study, since they still produce an accurate estimate of today's press costs.

A brief overview of Kang's calculation of required force is provided below. Resin can be expected to flow (1) radially outward from central sites or (2) inward from peripheral sites to a central sink. For radial flow outward from a central source, the required fill time is:

$$T_{fill} = \frac{\phi\mu}{2KP_{injection}}\left(R_{initial}^{2}\ln\left(\frac{R_{\max}}{R_{initial}}\right) - \frac{R_{initial}^{2} - R_{\max}^{2}}{2}\right)$$

And the maximum required mold force is:

$$F_{\max} = \pi P_{injection}\left(\frac{R_{initial}^{2} - R_{\max}^{2}}{2 * \ln\left(\frac{R_{\max}}{R_{initial}}\right)}\right)$$

For radial flow inward towards a central sink, the required fill time is:

$$T_{fill} = \frac{\phi\mu}{2KP_{injection}}\left(R_{initial}^{2}\ln\left(\frac{R_{initial}}{R_{\max}}\right) - \frac{R_{\max}^{2} - R_{initial}^{2}}{2}\right)$$

And the maximum required mold force is:

$$F_{\max} = \pi P_{injection}\left(\frac{R_{initial}^{2} - R_{\max}^{2}}{2 * \ln\left(\frac{R_{\max}}{R_{initial}}\right)}\right) + R_{initial}^{2}$$

Here K is the permeability, ϕ is the porosity, $R_{initial}$ is the radius of the dispenser's injection port, and R_{max} is the radius of the mold. For a more detailed discussion of these derivations from D'Arcy's Law on flow through porous media and associated assumptions, see Kang 2000.

The resin must be introduced at a sufficient number of sites throughout the mold for it to achieve an even distribution throughout the pre-form with the closing of the press. The number of dispensers required for successful resin distribution was provided by the ACC for the study, according to the size and geometry of each part. A regression of this data should be performed to enhance the model for future studies. The costs of the dispensers are based on previously collected data (Kang 1998).

Kang's tool costs for the SRIM mold were originally based on glass-reinforced parts. This regression of empirical data is as follows:

$$C_{tool,G} = 26300 + 71350 * W_G^{0.67} + 24800 * SA_G$$

For the carbon-reinforced components, the second coefficient was changed to compensate for the difference in material density from the glass-reinforced components:

$$C_{tool,C} = 26300 + 71350 * X^{-0.67} * W_C^{0.67} + 24800 * SA_G$$

The value of X is the same as used in the glass screen cost regression described in Section 4.4.3.1.

The SRIM cycle time consists of five stages: a 30 second load, a 20 second partial closing of the mold and injection of the resin, a 2.5 minute completion of the closing of the mold and cure of the resin, a 30 second opening of the mold and unloading of the part, and a 10 second clean and prep before the loading of the next part. This cycle time is the same for both the carbon- and the glass-reinforced parts in the model. It is held constant, regardless of part dimensions, by varying the number of dispensers such that sufficient resin can be injected within the time allowed for the second stage and that resin can then be evenly distributed throughout the reinforcement within the time the mold closes in the third stage.

4.4.3.4. Final Trimming and Inspection

After being unloaded from the press, the part is ready for final trimming and inspection. The final part trimming removes the resin flash escaped beyond the mold walls. This step is modeled as requiring 120 seconds during which 3% of the original material is removed.

4.4.4. Assembly

Although there are some examples of prior composite part sub-assemblies, there is to-date no experience in mass medium- to high-volume production of a composite unibody. There is not a general consensus on the most effective methods for assembling the components of a composite vehicle. In putting together the assembly model, all possible options were reviewed, both those available, and those under development. Based on this survey of methods, a single combination of methods was selected as most likely and feasible for a theoretical vehicle being assembled in the near future. Although an overview of all methods investigated and considered is presented below, modeling analyses were performed only on the combination of methods determined after consideration most feasible for mass production starting in 2010.

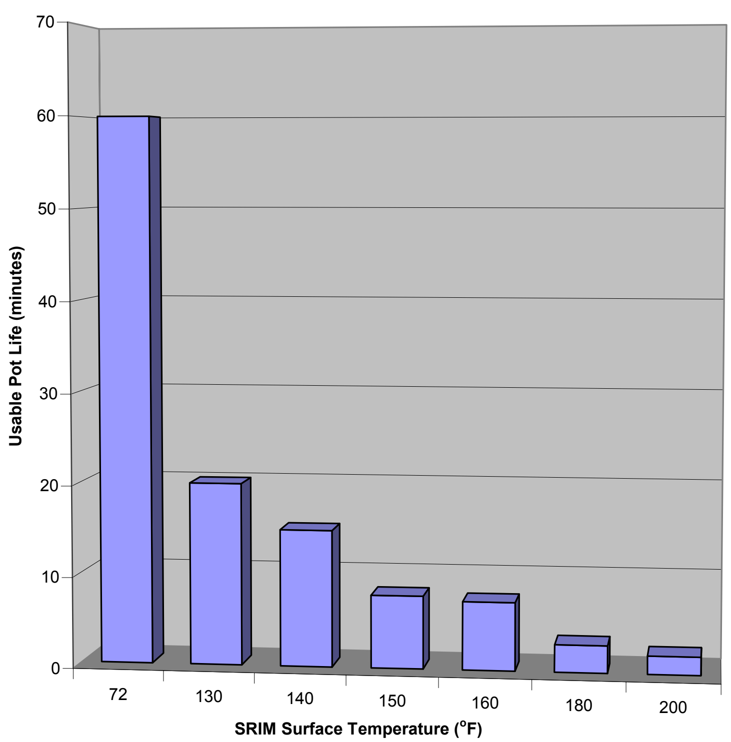
All of the assembly processes considered used adhesive or adhesive tape to bond the components, and required a follow-up step to cure the bond.

There were several different adhesive options. The only adhesive SIA considers appropriate for a structural application is a heat-cure epoxy. Although the heat cure requires additional equipment and time, it has superior properties to a room temperature epoxy. A heat cure epoxy does not have an open time – a limited time at room temperature during which adhesion to the other surface must occur for optimal join properties. This lack of open time increases flexibility in the length of adhesive which can be laid down at one time along the join, and in the number of parts which can be joined at a given station. A heat cured adhesive also has less scrap than a room temperature cured adhesive. In the case of a room temperature cured adhesive, the short open time causes a significant amount of material to build up and need to be purged from the dispenser. No primer is necessary on the joining surfaces of the part before laying down an epoxy adhesive. Cure time for a heat cured epoxy can range between one and seven minutes depending on the magnitude of heat used for cure. (See Table 8.) Longer cures lead to improved lap shear properties, but can be too expensive or impractical for higher production volumes. Typical cure times are two to three minutes. The useable pot life, or time the heat-cured epoxy adhesive can be in contact with air before losing necessary join properties, ranges from three minutes at 200°F to 60 minutes at room temperature. (See Figure 5.) The SIA recommended adhesive for structural composite applications is the Plastilock 731SI. This adhesive has been used in the GM truck box tailgate as well as in the Avalanche tailgate and midgate. The price for the 731SI provided by SIA for this study is $17.50/kg.

Table 8: Temperature Dependence of Cure Time for SIA's EXP-731E-SI Adhesive

Temperature (F)	Time (min)
300°	1
290°	1.5
260°	2
first half 260° / second half 140°	2.5
240°	5
230°	7

Figure 5: Surface Temperature Dependence of Pot Life for SIA's EXP-731E-SI Adhesive onto Pre-heated SRIM



Four other adhesive options are also worth mentioning. A "fusor" epoxy was suggested by GM to take advantage of RS induction to cure the epoxy (see discussion of RS induction curing later in this section). The only fusor epoxy to-date was developed by Lord Corporation for an application requiring the joining of one SMC and one SRIM part. The Lord fusor epoxy is doped with iron oxide. An alternative to epoxy is a urethane adhesive. Urethane adhesives cure at room temperature and cure faster than epoxies, but require a primer and produce a weaker bond. SIA recommends urethanes for field repair. The open time for urethanes tends to be around 30 minutes. Their gel time can be as little as 30 seconds to a few minutes. Urethanes also have the problem of being extremely moisture sensitive. In the GM minivan plant, foaming of the urethane adhesive occurred due to the plant's proximity to the ocean and lack of an internal climate control system. It is also important to keep in mind that whether urethane or epoxy, adhesives can be specially tailored to a specific application. For example, the SIA731SI was originally designed specifically for the GM truck box application. One final consideration is two-side adhesive tape. The applicability of such tape for structural join applications was, however, questioned, and further information not yet found.

The majority of the sources consulted – including Owens Corning, SIA, and Meridian – encouraged pre-heating the join surfaces before applying the adhesive. Pre-heat methods are identical to methods for curing the adhesive, after the joining of the parts. Pre-heat cycle times recommended were 80 to 95 seconds, at temperatures between 300^{o}F and 180^{o}F. The aim of the pre-heating is to be able to shorten cure times. Pre-heats are currently used in applications such as the GM 805 truck box, but not in low production volume full vehicle assemblies such as the GM Corvette. Sources with full-vehicle assembly experience expressed concern that pre-heating causes open-time problems for more complex joins. Such more complex joins would be necessary in assembling a full vehicle. Also, the 2-3 minutes required for cure without pre-heat do not create a bottleneck in assembly cycle times. A pre-heat was therefore not used in the modeled assembly steps for this study.

The bonding step in assembly entails positioning the first part or already-joined sub-assembly, laying down adhesive, and then positioning the second part or sub-assembly on top of the adhesive along the join. Bonding requires pumps, a metering system, adhesive guns, a heated hose, and switch-over pumps to carry out the dispensing of the adhesive. A standard hydraulic metering system is typically used for low production volumes at a cost of around $120K. A manifold system with a larger pump system and a vat of adhesive is typical for high annual production volumes (above 70K) at a cost of $300-350K. A mix tube is attached to the end of the adhesive robot, and the two components of the adhesive, supplied from different drums, are frequently pumped to the mix tube from a location elsewhere in the plant. The mix tube, which is 12-18" long, requires purging approximately once per shift. The purging takes around 10 minutes, and is accomplished by throwing out the mix tube ($2/tube) and replacing it with a new one. Approximately 1-5% of the epoxy in the process is lost through purging. The actual laying of the adhesive can be accomplished at about 0.3m per second. Additional time must be allotted for the robot switching between joins as well as for the beginning and end of each part's cycle, these additional time increments are estimated at two seconds per join and three seconds per cycle, respectively. Generally, around an 3/8" diameter bead is typical, although parts with bad tolerances can require up to a ½" bead, while parts with an extremely refined tolerance can require as small as 1/8" beads.

The most debate regarding the appropriate assembly methods for a composite unibody was around the methods and set-up for cure. In total, seven different cure methods were debated: hot blocks, hot air impingement, RS induction cure, radio frequency cure, microwave frequency cure, and oven curing. The majority of these cure methods, with the exception of oven curing, consist of attaching additional equipment to the fixture system holding the two assembly pieces together, and applying heat to the join line.

The hot blocks method is primarily applicable for low production volumes, although different sources disagree if appropriately low production volumes are 20K annually, 40K, or simply under 70K. It entails running oil, steam, or electricity through blocks held in contact with the join, when possible, on both sides. In the case of blocks heated with hot oil, a pump system is required, which is not required when using electricity or steam.

A second heating mechanism used with fixtures is hot air impingement. Hot air impingement consists of a large fan, which draws ambient air down through a tube into a heater. The heaters blow the heated air onto the bond line, and are generally placed every 50” along the join. Each heater costs between $8K and $12K. The system as a whole also requires a thermocouple sensor, as well as a control panel for the thermocoupler.

The local application of RS induction, radio frequencies or microwave frequencies to the bond line, either as a encompassing curing system, or as an initial “spot cure” method, have undergone and continue to undergo research and development within the industry. The largest advantage of induction, radio, or microwave heating methods are their potential for fast curing and for curing of limited locales along the join. Although it is easier to find an adhesive that responds to radio or microwave frequencies than to create an adhesive with metal doping which can be heated by induction, research suggests radio frequency alternatives to be sub-optimal in comparison to the other two, and industrial application of microwave frequencies is unlikely due to the shielding which would have to be set up for the workers to meet safety regulations. Although induction heating is definitely a future possibility, many obstacles remain. The metal doping of the adhesive requires a thicker bond line in order to get enough metal and adhesive into the join to enable the cure. The necessary metal doping has also been found, whether due to the thicker bond line or to the lack of homogeneity of the join, to affect the strength of the adhesive. Other problems have included induction's tendency to overheat and char thicker spots when the adhesive bead-size varies along the join, as well as problems with poor coupling. Owens Corning claims that induction heating was applied to the Camero Firebird in joining the door inner and outer, and is now also being looked at for the GM 800 truck box.

A final curing option is the use of large gas bake ovens. Generally, this option is impractical due to the associated space and expense of the oven itself and heating the entire parts rather than just the join. Although research is currently targeting eliminating the need for a post-bake, most of the adhesive systems currently require 35-40 minutes in an oven to complete the cure the remaining 30% to 40%. By leaving this post-bake until the end, it can be achieved in the paint ovens, without having to purchase extra equipment or add another step.

When joining parts or subassemblies, it is necessary to have a means for precisely bringing together the two parts after the adhesive is laid and then holding them in place until the cure is complete. The generally accepted method for holding the parts or subassemblies together is using fixtures. Two companies' cost estimates for fixtures, according to size are provided in Tables 9 and 10. Automated fixtures would bring the parts into place and close around them automatically, while the "non-automated" quotes represent fixtures placed with manual assistance.

Table 9: Fixture Costs, Based on Assembly Order Prototype II (Figure 6)

Scale	**Hot Blocks**		**Hot Air Impingement**		**Fixture Groups**
	Autom.	**Not Autom.***	**Autom.**	**Not Autom.***	
Small	$350K	$200K	$(350+75)K	$(200+75)K	B, D, A+B
Medium 1	$700K	$400K	$(700+200)K	$(400+200)K	A, 3
Medium 2	$725K	$500K	$(725+150)K	$(500+150)K	C1, C2
Large 1	$1.75M	$1.35M	$(1.75+0.3)M	$(1.35+0.3)M	1
Large 2	$1M	$750K	$(1+0.2)M	$(750+200)K	2

Figure 6: Assembly Order Prototype II

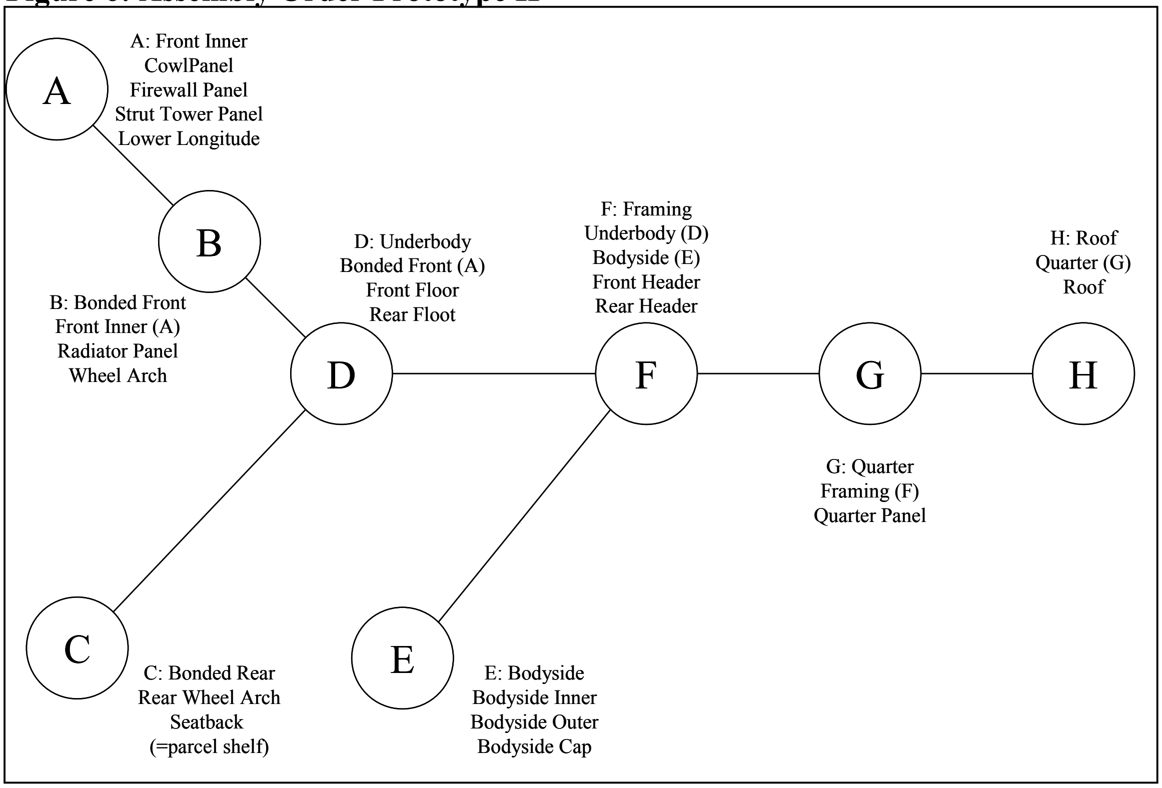


Table 10: Fixture Costs, Based on Final Modeled Assembly Order (Figure 4)

Scale	Curing System Cost	Fixture Cost	Total Cost	Included Assmb. Groups
Small	\$100K-\$200K	\$100K-250K	\$200K-\$450K	A, 1, 10
Medium	\$200K-250K	\$400K	\$600K-650K	B1+B2, 8+9
Large	\$250K-275K	\$750K-\$900K	\$1.025M-\$1.15M	2+3+4, 6+7

S-clips, U-clips, or rivets have been considered as an inexpensive alternative to fixtures to hold parts or sub-assemblies together until the adhesive has cured. Especially for thinner parts, S-clips, U-clips, or rivets, can lead to uneven pressure along the bond length during cure, and a less structurally sound join. Although rivets have been found not to cause any greater propagation of cracks or failure from their point source in reinforced composites than they would in steel, joins bonded using adhesive perform as well or better than joins bonded using rivets. One important function for rivets, however, is to be placed as a "stop" where the forces around a join seem to lend towards a "zipper effect" in crash tests.

The format of the assembly line is dependent on the number of parts, their shapes, as well as the tact time within which the final product must be produced. The number and lay-out of the stations is therefore determined by the required annual production volume and the available operating time per line, versus the time required to achieve the modeled operations of assembly. Larger production runs incorporate more stations, more robots, and more automation, while smaller production runs assume fewer stations, more time at each station, and more manual labor. Harsha Marti and Anil Jain, in their theses, provide a detailed description of the fundamentals and equations making up the general framework of the assembly model (Jain 1997) (Marti 1997).

5. Results

The sections below present the cost structure of production and assembly of the body-in-white (BIW) for a four-door sedan. As described in Chapter 4, the affect on this cost structure of different production materials – carbon-reinforced polyurethane structural reaction injected molded composite, glass-reinforced polyurethane structural reaction injected molded composite, and mild grade stamped steel; and of different production regions – the U.S. versus the P.R.C. – are observed. When presented in the results below, the carbon-reinforced polyurethane structural reaction injection molded composite is described with simply the word “carbon”, the glass-reinforced polyurethane structural reaction injected molded composite with the word “glass”, and the mild grade stamped steel with the word “steel”.

5.1. U.S. Cost Structure Breakdown

Given the different break-down of variable and fixed costs for a composite versus a steel BIW (see Figure 7), cost-competitiveness varies with production volume. At annual production volumes (APV) of 100,000, machine, equipment, building, maintenance, and overhead – all fixed expenses – make up 59% of steel BIW costs. These fixed expenses add up to only 32% of carbon, and 40% of glass BIW costs.

Figure 7: U.S. Body-in-White Production and Assembly Costs Breakdown
Annual Production Volume 100,000

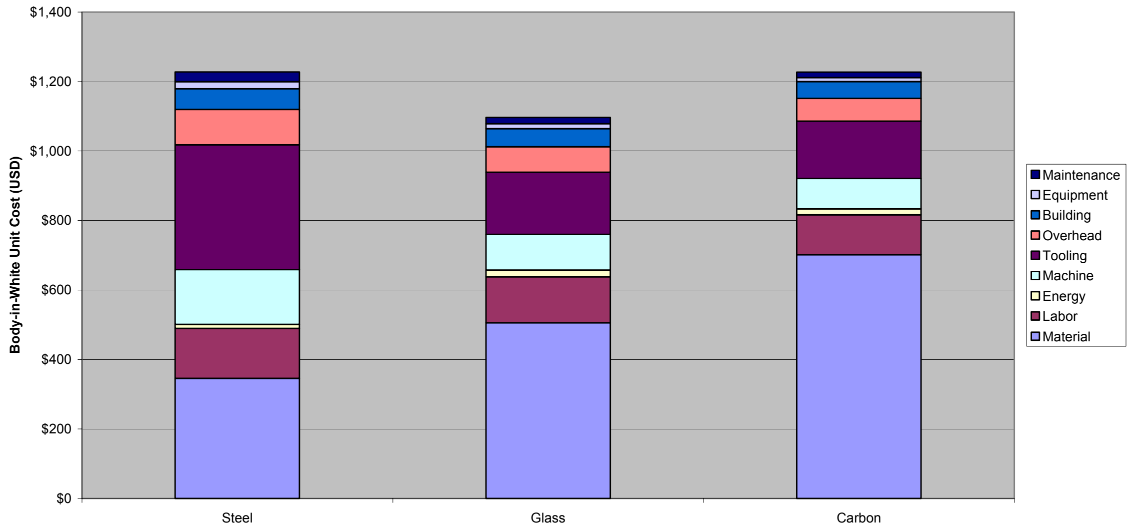
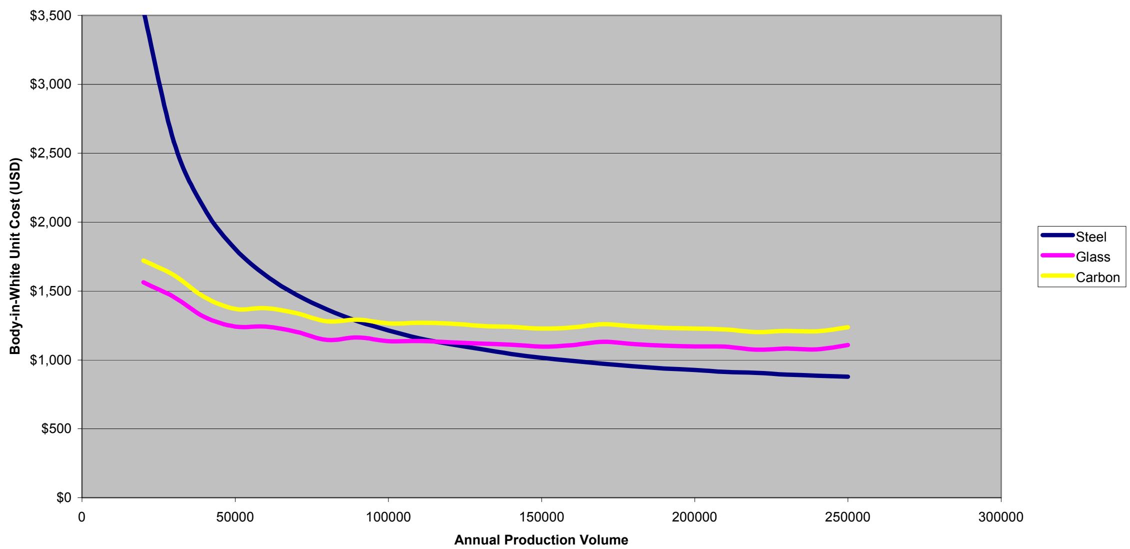


Figure 8 below shows the unit cost of producing and assembling a BIW in the U.S. Steel BIW costs range from $877/body unit at 250,000 APV to $3537/body unit at 20,000 APV. Carbon costs range from $1721/body unit to $1237/body unit, and glass from $1563/body unit to $1107/body unit at those same production volumes. At annual production volumes under 120,000, the glass-reinforced BIW is more competitive than the steel, and at annual production volumes under 90,000, the carbon-reinforced BIW is also more competitive.

Figure 8: U.S. Body-in-White Production and Assembly



Isolating the component production and assembly costs, Figure 9 shows that despite there being only 25 components and 37 inserts required for a composite BIW compared with 120 components and 130 inserts for steel, the sum of the composite component plus insert costs adds up to significantly more than the sum of the steel component plus insert costs (so long as annual production volumes are above 30,000 for glass and 22,000 for carbon). The assembly of only 25 parts, as can be seen in Figure 10, manages to make up the difference in component costs, up to the annual production volume crossover points for each composite, as already discussed for Figure 8.

Figure 9: U.S. Body-in-White Component and Insert Production

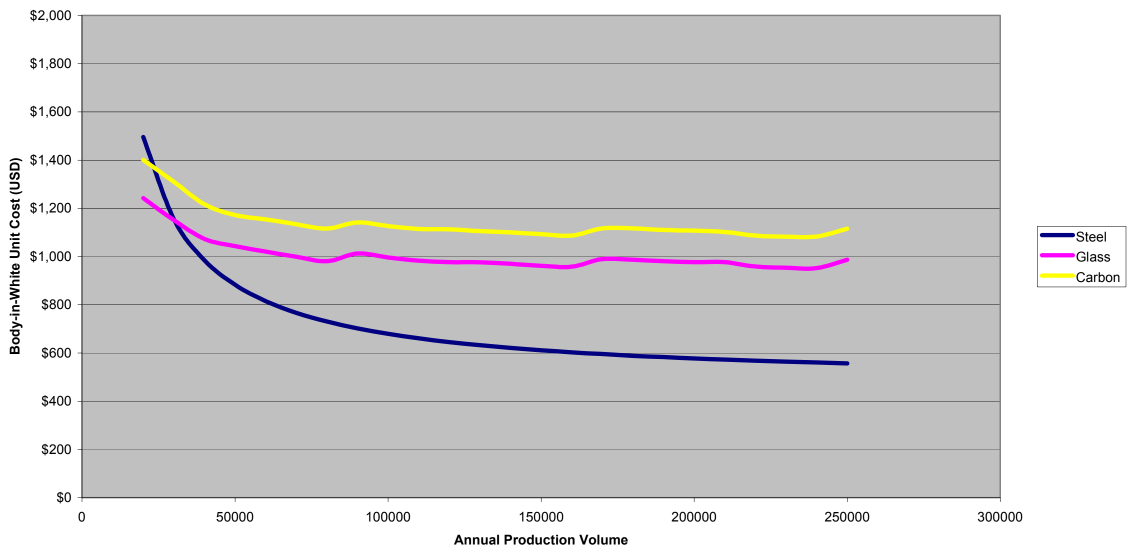
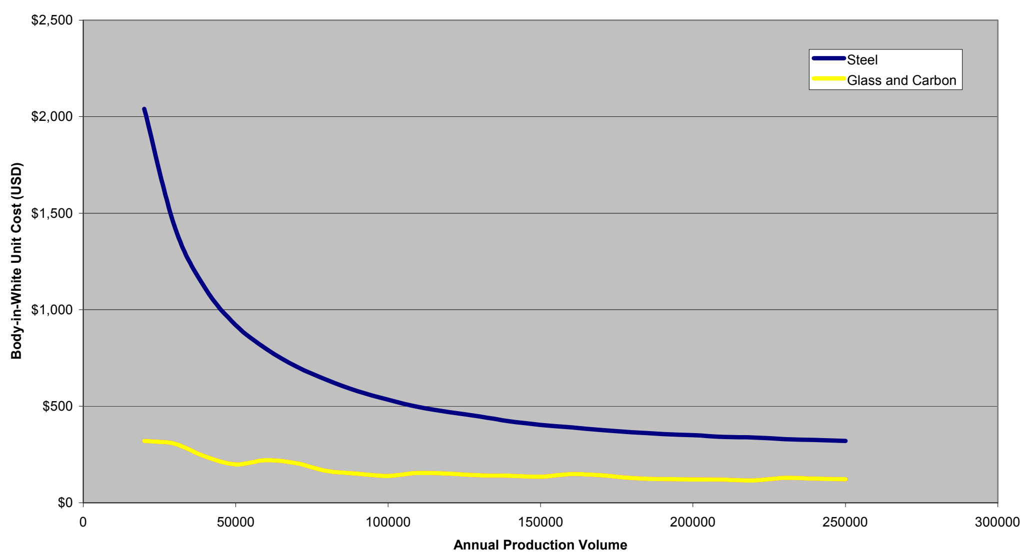


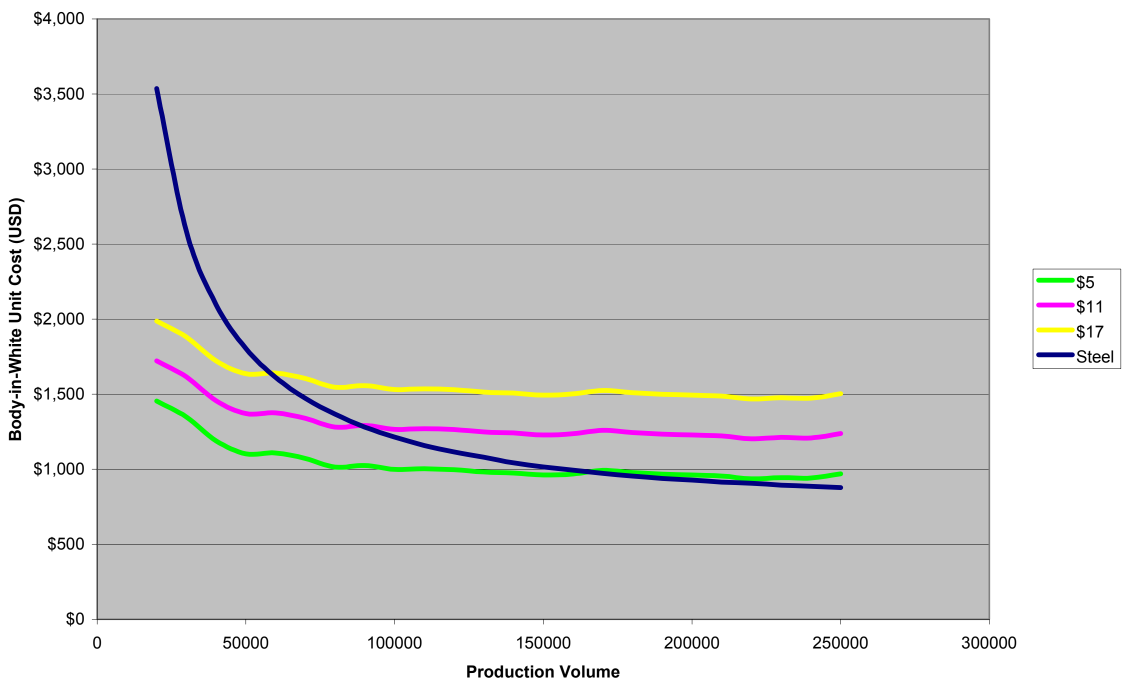
Figure 10: U.S. Body-in-White Assembly



Looking again at Figure 7, material prices, at 57%, clearly dominate the carbon BIW costs. Of these material costs, 76% is alone the cost of the carbon fiber. Although carbon fiber market prices are currently quoted at $11.05/kg, changes in magnitudes of demand and in suppliers' composite fiber production capabilities could lead to changes in price. Figure 10 shows that a

$12/kg fluctuation ($6/kg increase or decrease) in carbon fiber prices can bring about a $532 change in carbon BIW unit costs. This difference amounts to carbon using $17/kg reinforcement prices only being more cost-competitive than steel up to 60,000 body units per year, while carbon using $5/kg reinforcement prices remains more cost competitive than steel up to 170,000 body units per year.

Figure 11: Body-in-White Cost Sensitivity to Carbon Fiber Prices



Neither scrap rates during pre-forming (Figure 12) nor adhesive prices for assembly (Figure 14) have a significant impact on the cost-competitiveness of the carbon BIW against steel. The reject rate during injection molding has a slightly larger impact (Figure 13), a seven percent increase changing the crossover point by 10,000 APV, and the cost by $124.

Figure 12: Body-in-White Cost Sensitivity to Preforming Scrap Rates

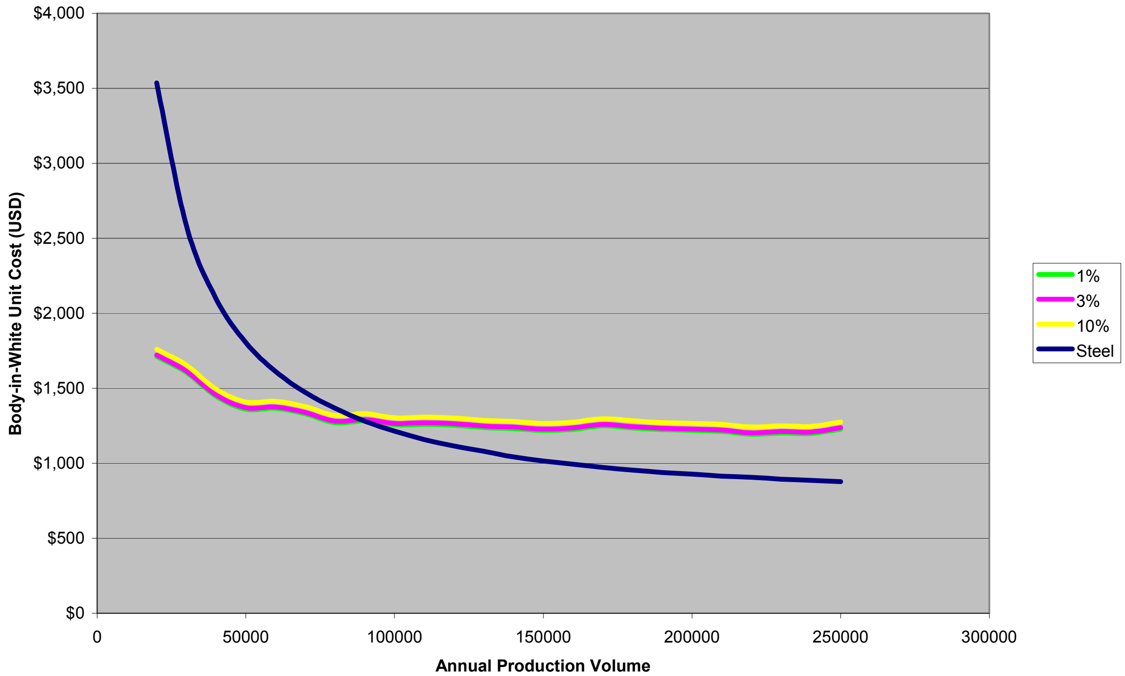


Figure 13: Body-in-White Cost Sensitivity to Injection Molding Reject Rates

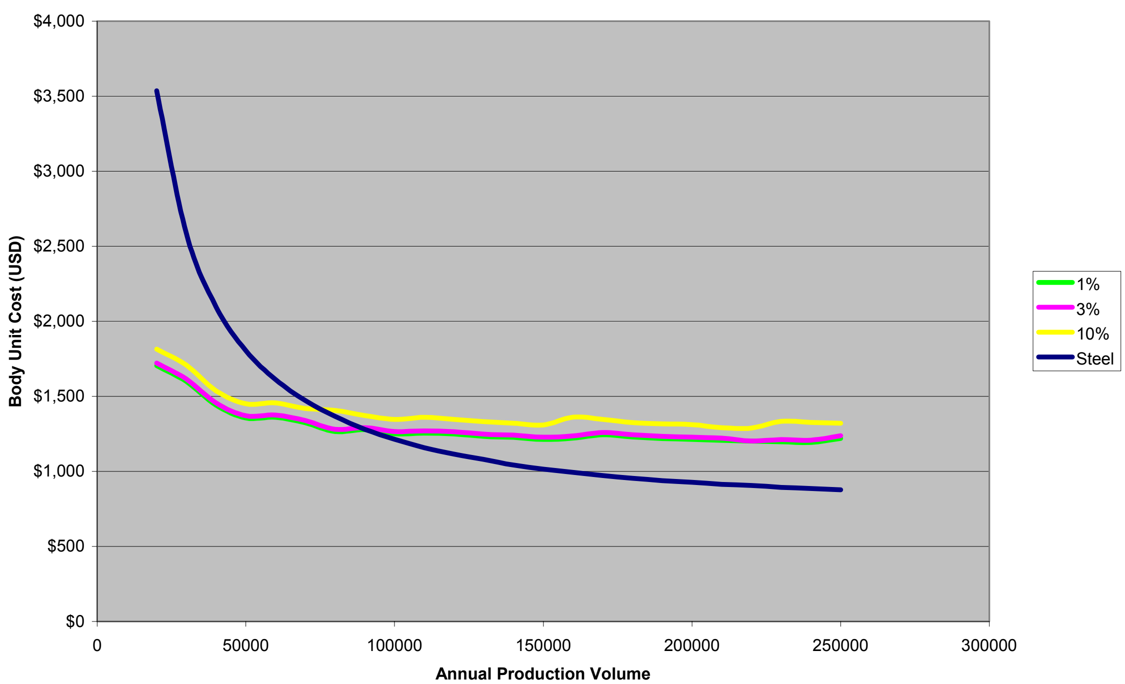
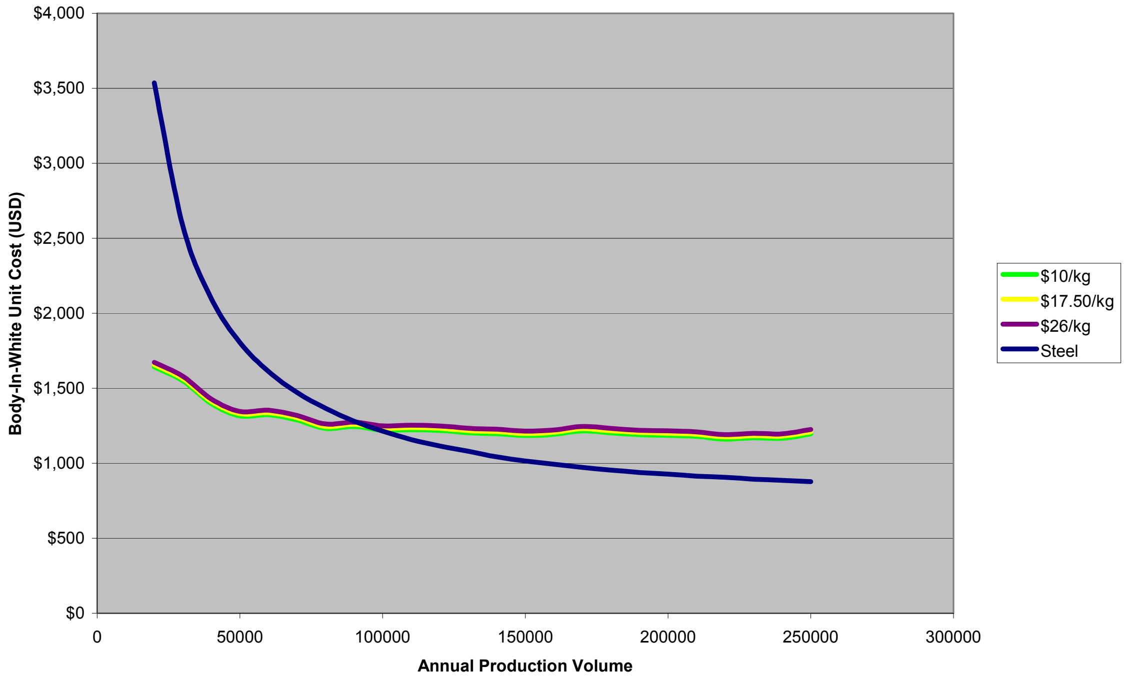


Figure 14: Body-In-White Cost Sensitivity to Adhesive Price



5.2. P.R.C. Cost Structure Breakdown

The cost breakdown of production and assembly being performed in the P.R.C. is slightly different than that discussed for the U.S. At annual production volumes (APV) of 100,000 complete steel BIWs', fixed expenses make up 63% of overall costs (compared with 59% in the U.S.) according to assumptions associated with locating the production and assembly in the P.R.C. instead of the U.S. Fixed expenses add up to 36% of carbon, and 47% of glass BIW costs, (compared when 32% and 40% in the U.S.) when producing in the P.R.C.

Figure 15: P.R.C. Body-in-White Production and Assembly Cost Breakdown
Annual Production Volume 100,000

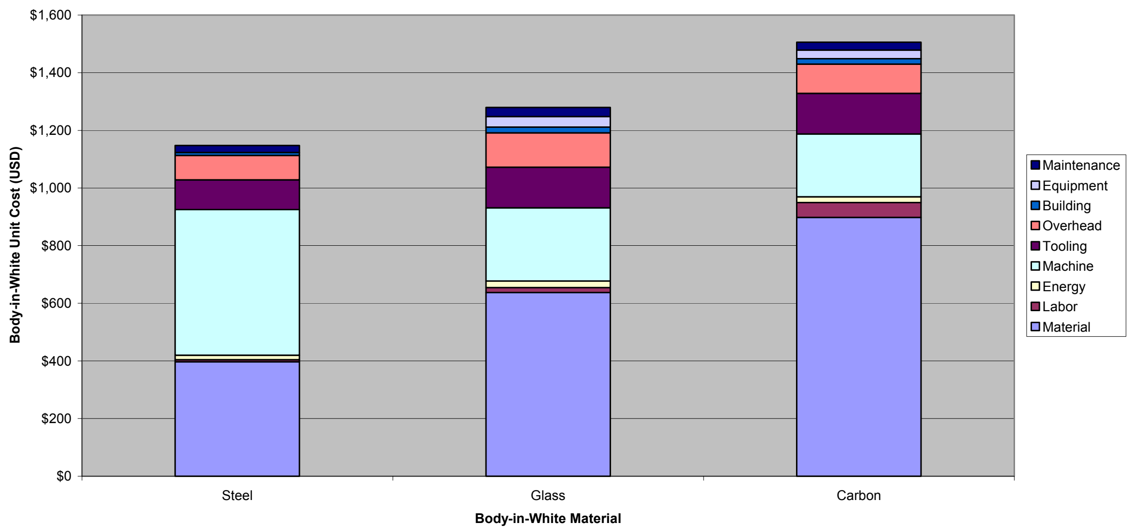
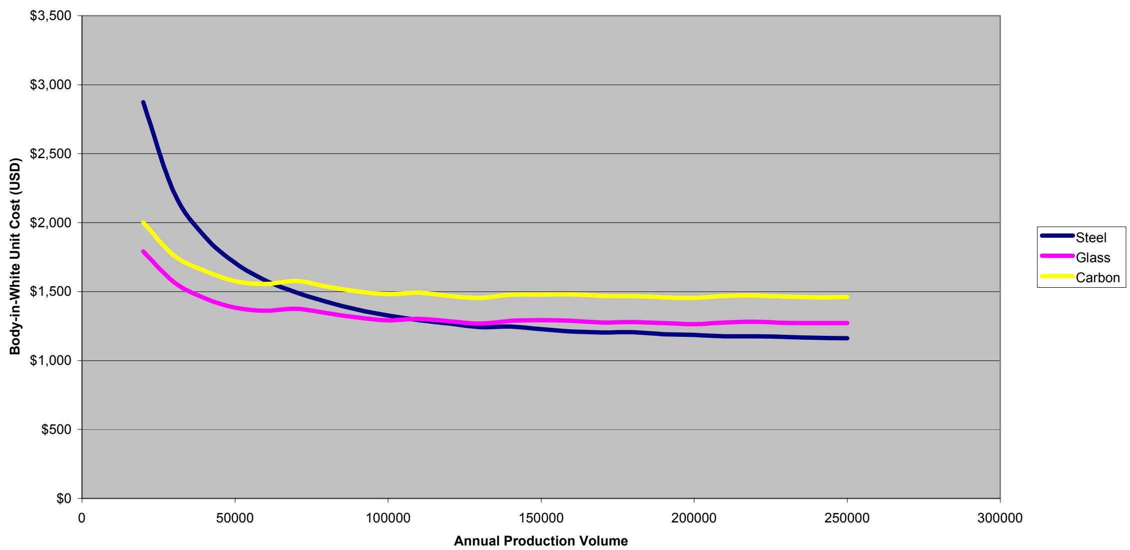


Figure 16 shows that at annual production volumes under 110,000, the glass-reinforced BIW is more competitive than the steel, and at annual production volumes under 65,000, the carbon-reinforced BIW is also more competitive. These crossovers can be compared with a steel-glass crossover of 120,000, and a steel-carbon crossover of 90,000 in the U.S. Throughout the plot, the P.R.C.'s cost curves are higher than the U.S.'s for all three materials. These higher costs come about due to the increases in capital recovery rate, material costs, machine costs, and downtimes, as well as decreases in component plant utilization outweighing the significantly lower cost of tools in the overall cost of the final, assembled BIW. Comparatively, the steel BIW fares better against the composites in the P.R.C. than it does in the U.S. When manufacturing in the P.R.C., the larger role of tooling in overall costs enables steel to be more cost-competitive than the material-cost-burdened composites, despite the added burden of steel's large capital costs. Labor for the three materials comes out approximately the same – steel having larger assembly labor requirements, and composites larger component production labor requirements.

For all three materials, the reduced labor costs in the P.R.C. are insignificant in comparison to the impact of changes in material costs and burdens put on capital costs.

Figure 16: P.R.C. Body-in-White Production and Assembly



Isolating the component production from assembly shows that although the glass BIW component production is less competitive against steel than it was in the U.S. at lower production volumes, it is more competitive compared to its performance against steel in the U.S. at higher production volumes. This difference is caused by the difference between the proportion of costs taken up by capital costs between glass and steel being less in the P.R.C. (APV 100,000: steel fixed 63%, glass fixed 47%, delta=16%) than in the U.S. (APV 100,000: steel fixed 59%, glass fixed 40%, delta=19%). The composite advantage for assembly is at low production volumes less significant when manufacturing in the P.RC. This decreased advantage comes from the savings on the larger labor requirements to assemble the steel BIW.

Figure 17: P.R.C. Body-in-White Component and Insert Production

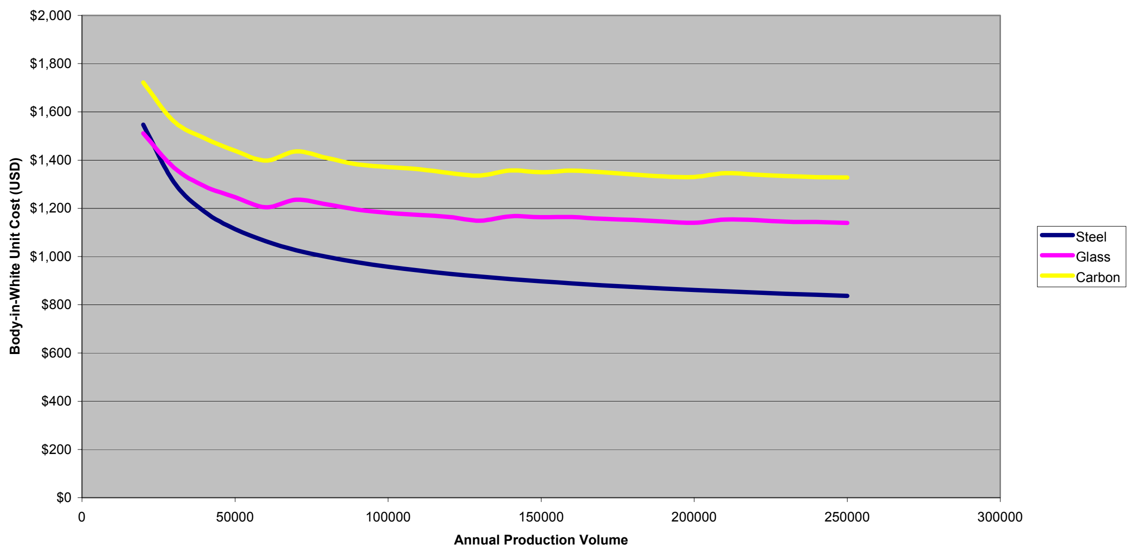
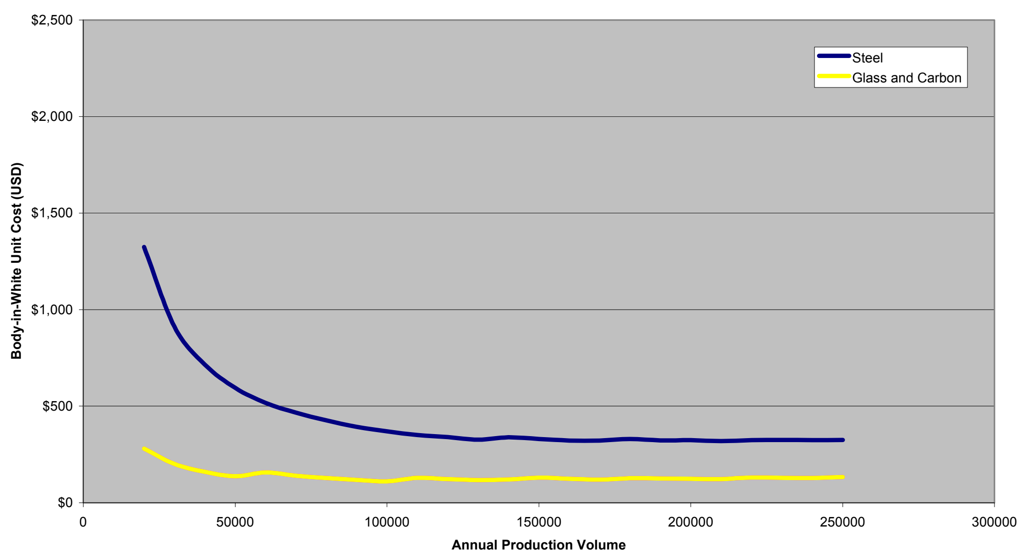


Figure 18: P.R.C. Body-in-White Assembly



As discussed in Chapter 4, two additional scenarios were run on the P.R.C. model, to better understand both how the position of BIWs manufactured in China versus in the U.S. could change in the future, as well as to better understand how the position of glass and carbon composites versus steel within the P.R.C. might change. Figure 19 shows the competitiveness of composites with a 1% decrease in capital recovery rates, downtimes only 20% instead of 30% higher, material costs the same instead of higher, machine costs still 17.5% higher, and utilization 30% below instead of 50% below the 100% expected in the U.S. Although the crossover for the composites with steel is lower, all three curves remain relatively flat at higher production volumes, with the glass composite line only rising to $196 more than steel at annual production volumes of 250,000. The crossovers are 80,000 APV for glass and 60,000 APV for carbon.

Figure 19: Conservative Estimate of Future P.R.C. Body-in-White Production and Assembly Costs

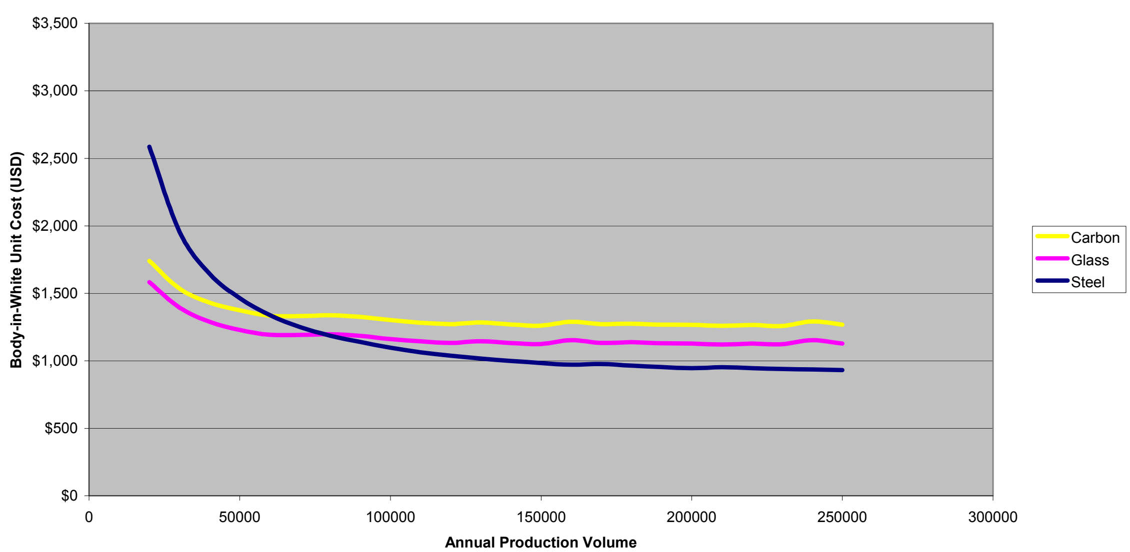
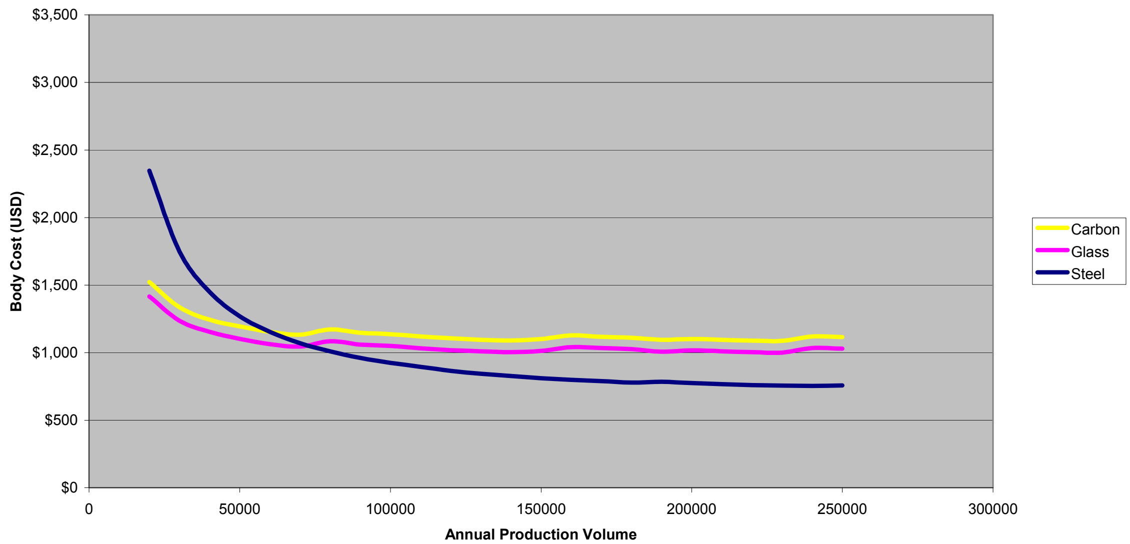


Figure 20 shows the competitiveness of composites with a 2% decrease in capital recovery rates, downtimes only 10% instead of 30% higher, material costs 12.5% cheaper than in the U.S., machine costs still 17.5% higher, and utilization 10% below the 100% expected in the U.S. Under this scenario, steel becomes even more competitive. Although steel's actual crossover with carbon remains the same, it becomes more competitive at higher production volumes. For glass, the steel crossover goes down to 70,000 APV, and then continues to be more competitive than it was in the "now" scenario at higher production volumes.

Figure 20: Optimistic Estimate of Future P.R.C. Body-in-White Production and Assembly Costs



It is useful to compare all four scenarios: U.S., P.R.C. now, P.R.C. future conservative, and P.R.C. future optimistic. (See Section 4.2. Table 5.) The steady decline in the steel-glass crossovers is shown in Figure 21. The cost-benefits of the improving free-capacity utilization and the lessening burden on capital costs makes steel progressively more competitive at lower production volumes. Steel is most competitive against glass in the U.S. scenario, where there is full free capacity utilization and the least capital burden (capital recovery rate of 12%, downtime 20%, no additional mark-up on machines). Although total material costs decrease from the "now" to the "future conservative" to the "future optimistic" scenario for glass composites, the cost benefits of these decreases in material costs fail to outweigh the cost benefits conferred on steel in the same scenarios. For carbon, the crossovers also decline (see Figure 22). In the case of the material-cost-burdened carbon, however, the reduction of material costs is significant enough keeps the crossover between the conservative and the optimistic scenarios constant.

Figure 21: Sensitivity of P.R.C. Steel-Glass Cost Parity to Varying Assumptions

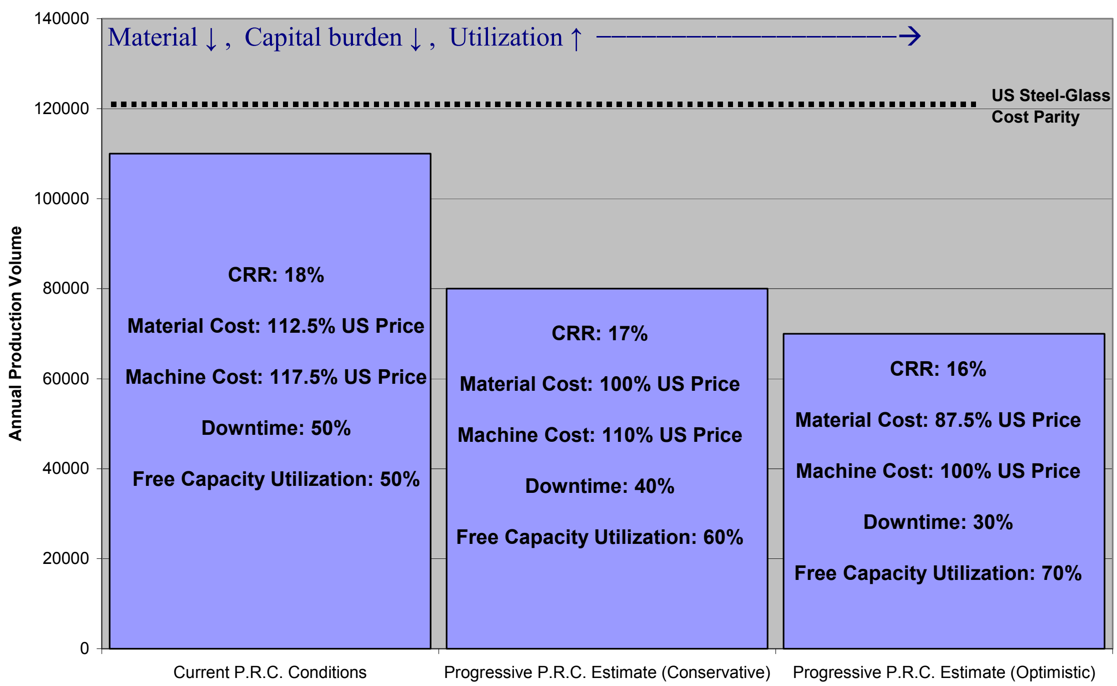
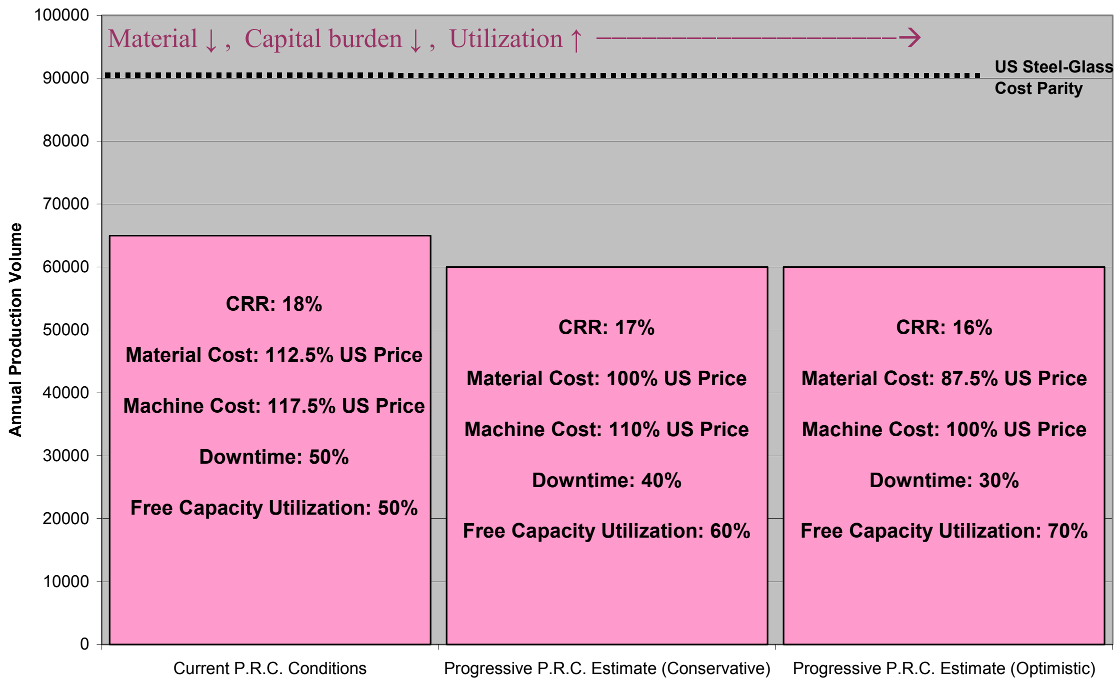


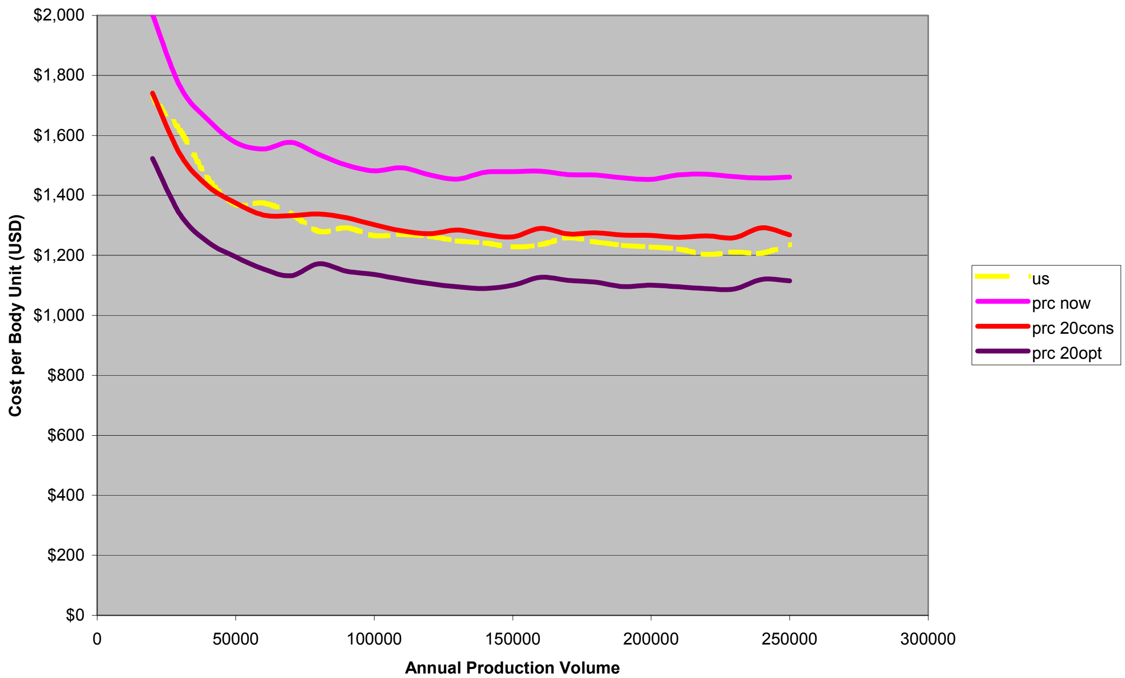
Figure 22: Sensitivity of P.R.C. Steel-Carbon Cost Parity to Varying Assumptions



5.3. Comparison of U.S. and China

A second point of interest is how BIW costs in one country compare against those costs for producing the same material BIW in the other country. In this analysis, both carbon and glass perform very similarly. (See Figures 23 and 24.) For the current environment in the P.R.C. ("prc now", Figures 21-25), production of the composite BIW is more expensive in China than in the U.S. – for carbon, on average $226 more expensive, and for glass, on average $168 more expensive. For the conservative future scenario, both composite materials have approximately the same production plus assembly costs in the U.S. and China. For the optimistic future scenarios, the production plus assembly costs in China come out cheaper than those in the U.S. For carbon these costs come out on average $151 cheaper, for glass, on average $106 cheaper.

Figure 23: Carbon US vs PRC Comparison



Steel performs differently than the composites when comparing its costs in the U.S. versus China. (See Figure 25.) According to the assumptions for steel BIW manufacturing in the U.S. versus currently in China, the cost of a BIW is already cheaper in the P.R.C. at annual production volumes under 70,000. At the conservative future assumptions, the P.R.C. manufactured BIW is cheaper below 170,000 APV, and remains approximately equal to the U.S. costs above 170,000 APV. At the optimistic future assumptions, the P.R.C. manufactured BIW is cheaper at all production volumes.

Figure 24: Glass US vs PRC Comparison

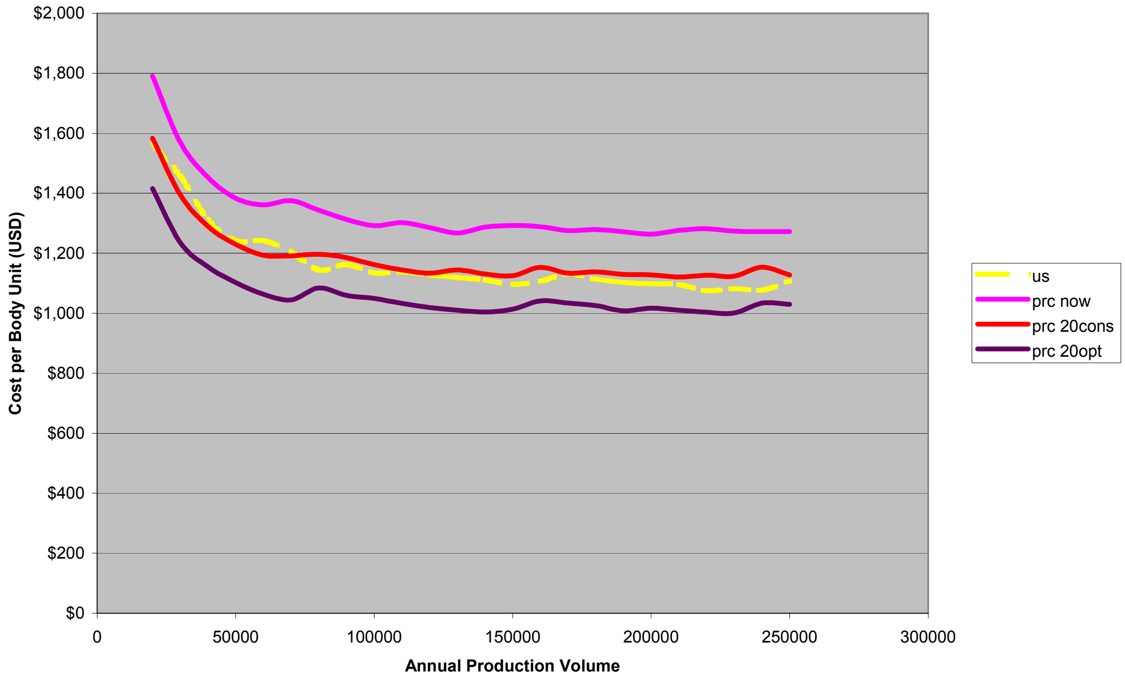
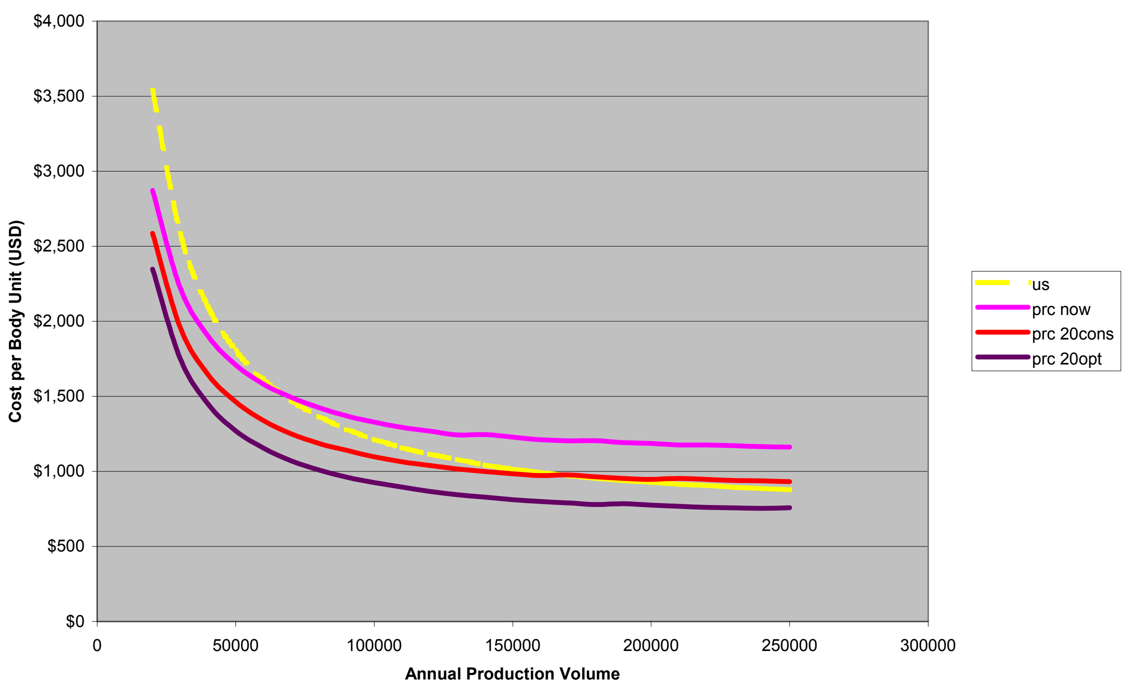


Figure 25: Steel US vs PRC Comparison



In an attempt to better understand the significance of the assumptions made for the different P.R.C. scenarios chosen, as well as to better understand the sensitivity of the BIW costs to changes over time in the P.R.C., a final set of analyses were run. Five sensitivities were run on the P.R.C. model. The range of these sensitivities is shown in Table 11 below.

Table 11: Variation of Variables Run in P.R.C. Model Sensitivities.

	Low	P.R.C. "Now" Case	High
CRR	12%	18%	20%
Material Costs	80% US price	112.5% US price	120% US price
Machine Costs	90% US price	117.5% US price	125% US price
Downtime	70%	50%	30%
Free Capacity Utilization	40%	50%	90%

The impact of the variations in Table 11 on body-in-white unit costs can be seen for carbon-reinforced composite, glass-reinforced composite, and steel BIWs, in Figures 26, 27, and 28, respectively. Material price variations have the largest impact on carbon BIW costs (Figure 26). The variations in capital recovery rate (CRR), machine costs, downtime, and utilization all have a large impact on steel production costs (Figure 28). Of all the variables, downtime had the largest impact on cost for all three materials. For both glass and steel, the variable with the next largest impact was the capital recovery rate, whereas for carbon, the variable with the next largest impact was material. For glass and carbon, utilization had the lowest impact, while for steel, material prices had the lowest impact on final BIW costs.

Figure 26: Carbon Body-In-White Cost Sensitivity to Percentage Variation from Base Case
Annual Production Volume 100,000

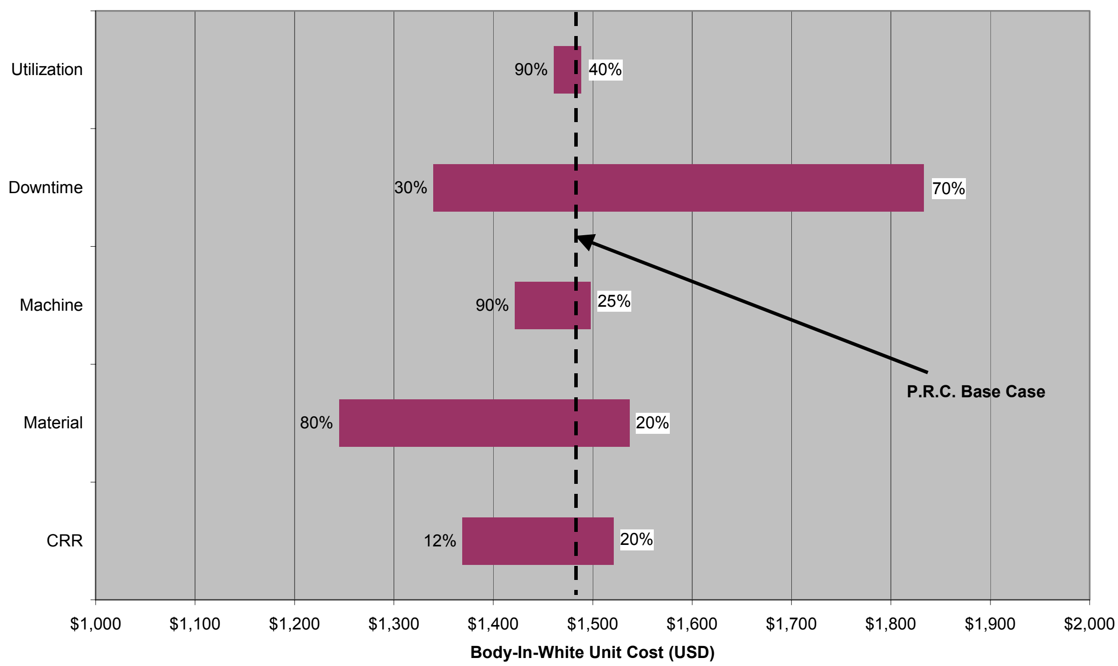


Figure 27: Glass Body-In-White Cost Sensitivity to Percentage Variation from Base Case
Annual Production Volume 100,000

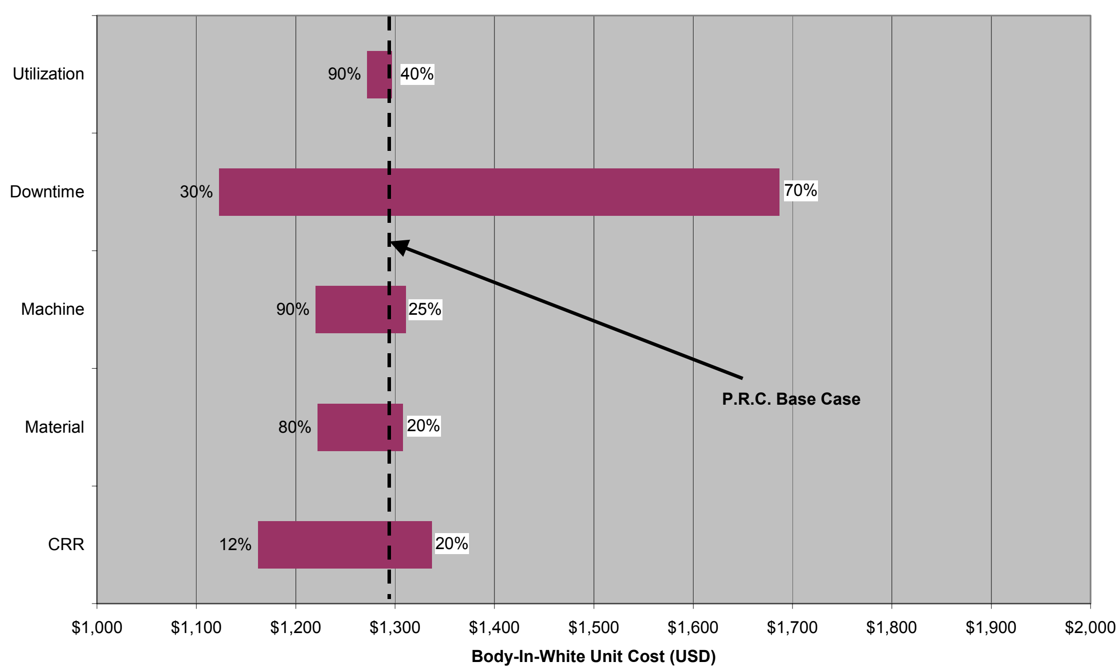
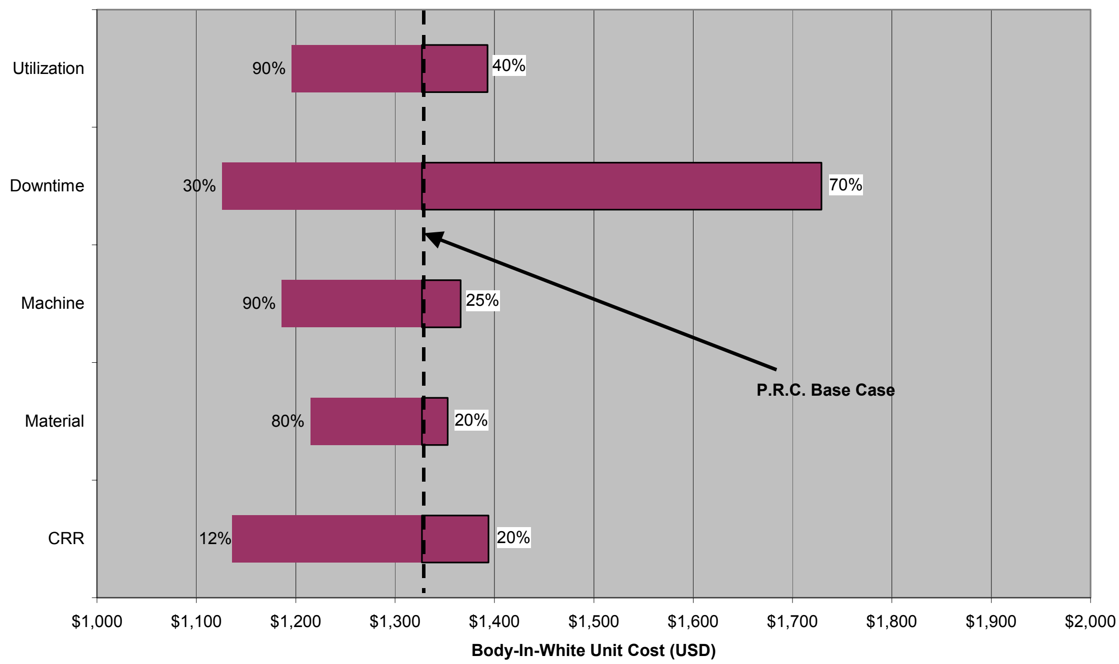
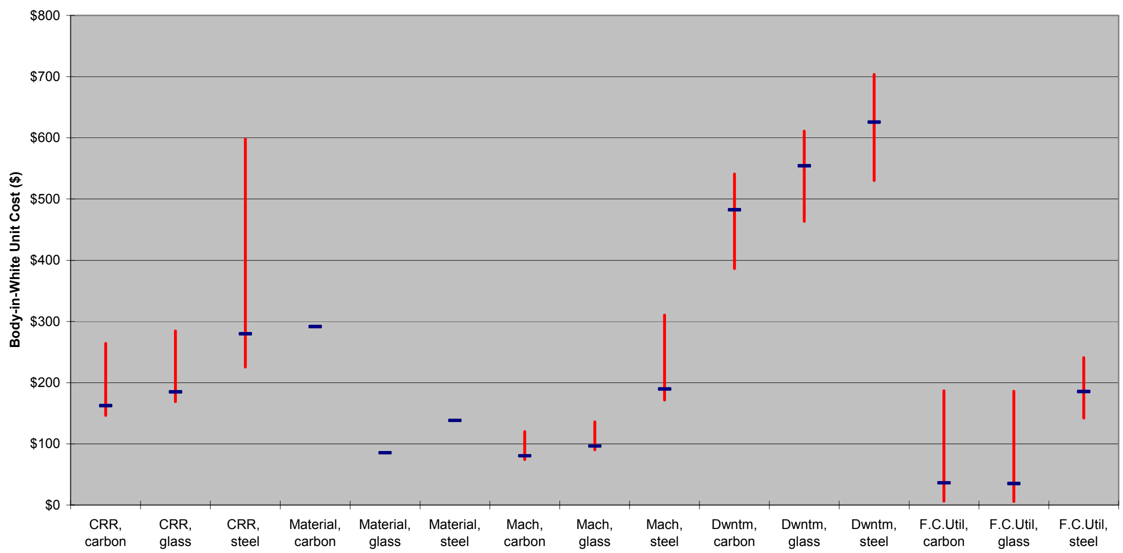


Figure 28: Steel Body-In-White Cost Sensitivity to Percentage Variation from Base Case
Annual Production Volume 100,000



The BIW cost with each variable within the variable's sensitivity range was plotted from 20,000 APV to 250,000 APV. This plotting created a set of curves showing how the extent of impact the chosen variation of each variable might vary across annual production volumes. In Figure 29, the horizontal blue lines represent the average cost impact across all annual production volumes of the variable ranges shown in Table 11. The red lines represent the impact of annual production volume on each variable range's impact on cost. The variable whose cost impact differs the most with annual production volume is capital recovery rate in the case of the steel BIW. The cost impact of downtime variations and the cost impact of free capacity utilization variations differ greatly with annual production volume for all three materials.

Figure 29: Sensitivity of BIW Variable Cost Sensitivity to Annual Production Volume



6. Discussion

6.1 U.S. Discussion

Typical production volumes for a vehicle on the U.S. market vary greatly. GM produced 32,555 Corvettes versus 238,225 Cavaliers domestically in 2002. Of vehicle bodies produced in North America in 2002, 78% of car models and 72% of truck models have annual production volumes under 120,000 – the cross-over point between glass and steel. During that same period, 66% of car models and 63% of truck models have annual production volumes under 90,000, the carbon cross-over point. (AutomotiveNews 2003). Figures 30 and 31 present the distribution of 2002 production volumes for North-American produced vehicle models alongside the original composite-steel cross-over points presented in Chapter 5 (Chapter 5, Figure 8).

Figure 30: North American Vehicle Production Volumes:
Number of Models with Volumes Below Composite-Steel Cost Parity
(Steel, Glass, Carbon Vehicle Costs plotted versus 2nd Y Axis)

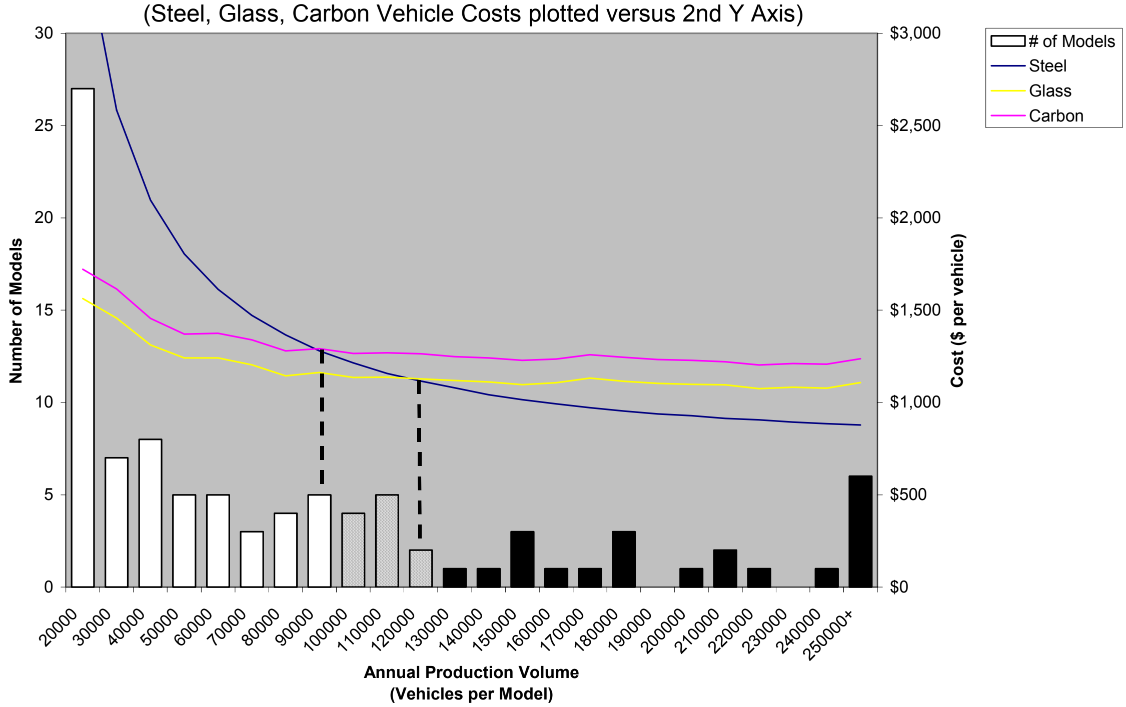
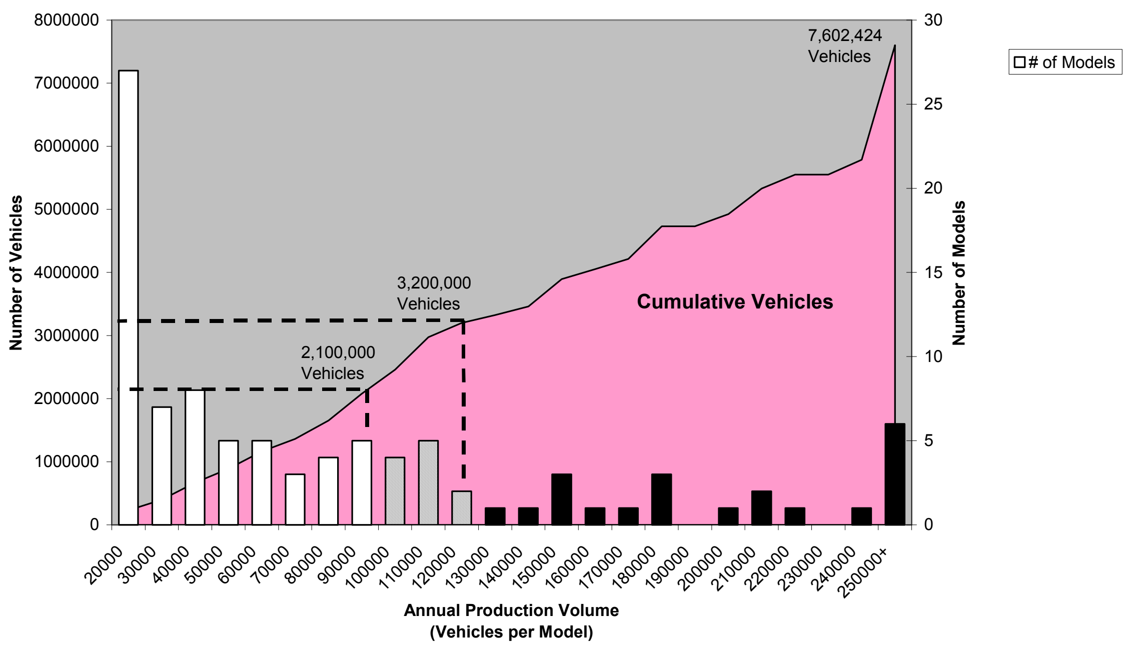


Figure 31: North America Vehicle Production Volumes
Total Vehicles More Competitive with Composites than with Steel
(Colums, Representing Number of Models, Are Plotted vs. 2nd Y Axis)

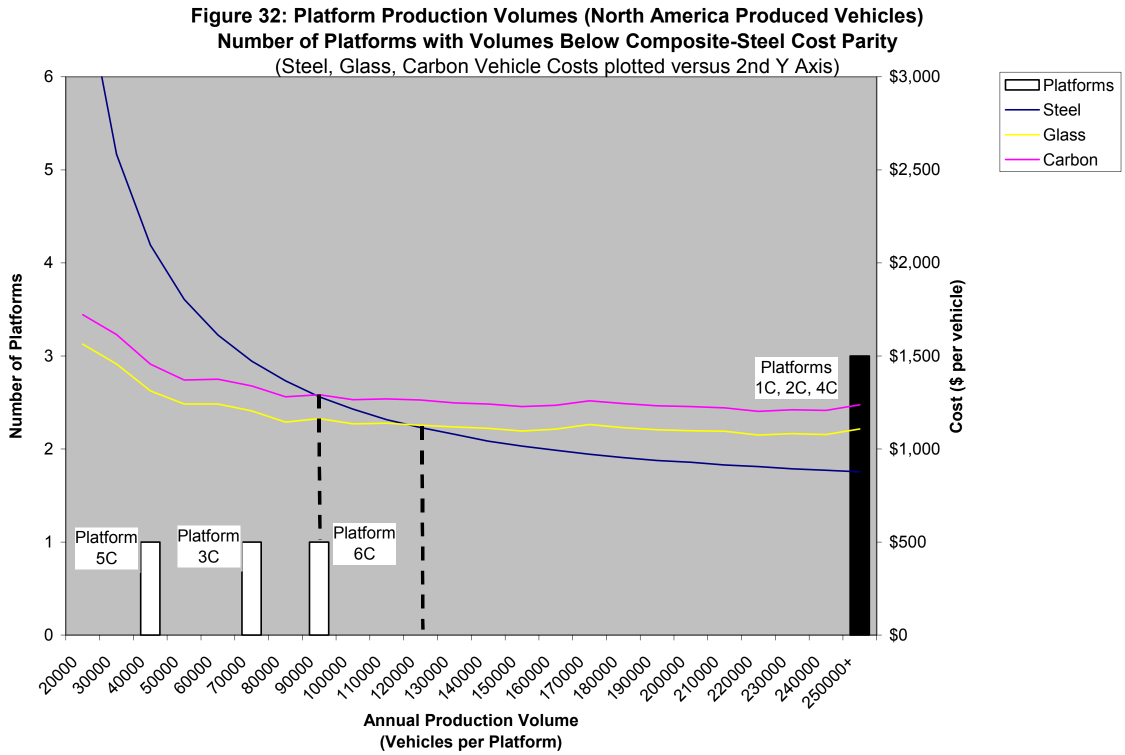


Figures 30 and 31 provide a first-cut estimate for composite competitiveness. Some components, however, are shared across model platforms, causing the relevant production volume across which to spread capital equipment costs potentially higher. An analysis of GM's North American production suggested that cars could be grouped into six groups according to sharing of component platforms, and trucks could be grouped into nine groups according to sharing of component platforms. Vehicles within each of the groups share approximately 50% by mass of their body platforms, if a car group, and 65% by mass of their body platforms, if a truck group.[8] The production volumes of the six car and 9 truck platform-sharing groups can be seen in table 12. Even accounting for part sharing using this scheme, some 22% of car models, making up 11% of total U.S. annual new vehicle car production, had annual production volumes under 120,000 (the U.S. production crossover point for glass reinforced composite with steel). These same percentages held for production volumes under 90,000 annually, the U.S. production crossover point for carbon reinforced composite with steel. 16% of truck models, making up 9% of total U.S. annual new vehicle truck production, had annual production volumes under 120,000 (the U.S. production crossover point for glass reinforced composite with steel) even for their shared component groups. 9% of truck models, making up 5% of total U.S. annual new vehicle truck production, had annual production volumes under 90,000, (the U.S. production crossover point for carbon reinforced composite with steel) even for their shared component groups.

[8] Platform sharing in the groups when looking at the whole vehicle (not just the body) was higher, ranging between 70% and 85%, depending on the group.

Table 12: Car and truck model groupings according to platform sharing

Platform	Platform Type	Vehicles Sharing Platform	Total Vehicles Produced Annually
1C	Car	Century, Regal, Impala/Lumina, Monte Carlo, Intrigue, Grand Prix	702,738
2C	Car	LeSabre, Park Avenue, DeVille, Eldorado, Aurora, Bonneville	310,381
3C	Car	CTS, Seville	70,500
4C	Car	Cavalier, Sunfire, Ion, S Series	548,775
5C	Car	Corvette	35,938
6C	Car	Joy/Swing, Monza	86,983
1T	Truck	Rendevous, Aztek,	112,020
2T	Truck	Escalade, EscaladeESV, EscaladeEXT, Avalanche, Silverado, Suburban, Tahoe, Yukon, YukonXL	1,679,809
3T	Truck	Blazer, S10, Jimmy, Sonoma	288,081
4T	Truck	SSR	5
5T	Truck	TrailBlazer, TrailBlazerEXT, Envoy, EnvoyXL, Bravada, Isuzu Ascender	446,133
6T	Truck	Venture, Silhoutte, Montana	238,609
7T	Truck	Safari	76,586
8T	Truck	Express, Savana	146,140
9T	Truck	Vue	87,883



A final decision as to which components to make out of steel versus which to make out of composite would require assessing cost-competitiveness at the appropriate vehicle or platform production volume of each subassembly. The results presented in Chapter 5, regarding the relevant competitiveness of steel, carbon-reinforced, and glass-reinforced BIWs, are only relevant for a BIW constructed entirely of the respective material, and not for the cost-competitiveness of individual subassemblies. Only at U.S. annual production volumes below 30,000 for glass composite components and below 20,000 for carbon composite components is the production of composite components less expensive than steel. At these low production volumes, it would be possible to substitute composite for steel components in a body-in-white for, for example, light-weighting purposes, without assembly or consolidation of parts benefits being necessary to achieve cost-competitiveness. At higher production volumes, composites only begin to gain cost-advantage at the sub-assembly level. This advantage does not exist within all sub-assemblies. Work-to-date has shown both the roof and the bodyside subassemblies are cheaper in steel than in composites for all production volumes. Kang's 1998 thesis discusses a cost-optimizing body-in-white combining composite and steel subassemblies. Further study is required to find the ACC Focal Project III subassemblies which are more cost competitive out of composite versus those more cost-competitive out of steel, given appropriate vehicle or platform-sharing production volumes.

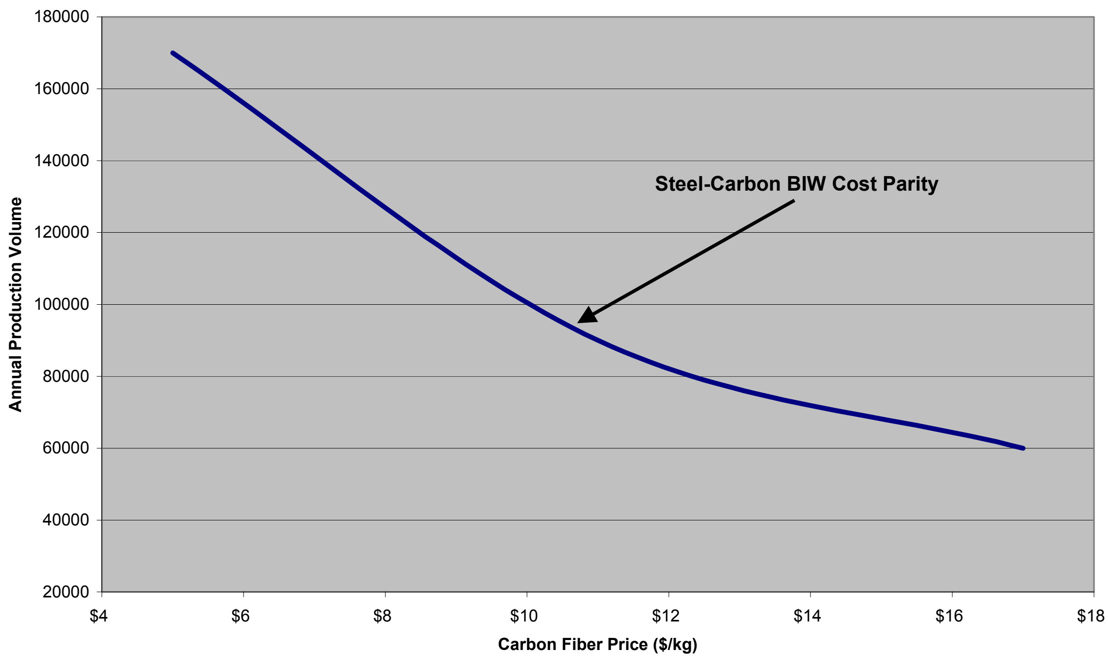
Future analysis of the cost-competitiveness of composites versus steel at the individual sub-assembly level incorporating platform-sharing considerations as well as hybrid-material options for the BIW would provide extensive insights. As a first cut, the above review of annual new vehicle production in the U.S. suggests, that from a production cost perspective over 70% of current vehicle models should be being evaluated for composite-steel hybrid body-in-whites, and 16% of truck and 22% of car models should be being considered for entirely composite body-in-whites. Industry trends indicate that these values will only increase as build-to-order and custom initiatives lead to an increase in the number of distinct models, and, therefore, a decrease in the production volumes for individual components.

A Re-Assessment of U.S. Variable Assumptions

Scrap rates, reject rates, and adhesive costs, as shown in the sensitivities in Figures 12, 13, and 14 in Chapter 4, all have little impact on overall costs, regardless of annual production volumes. As such, within the annual production volume ranges explored, neither scrap rates, nor reject rates, nor adhesive costs should be of immediate concern in the interest of minimizing manufacturing costs.

Materials make up 57% of the overall costs of the carbon-reinforced BIW. At a price of $11/kg, carbon fiber makes up 76% of these material costs. The market price of carbon fiber thus has a huge impact on the cost-feasibility of producing a carbon-fiber reinforced BIW, and is worth scrutinizing here in greater depth. Car manufacturers claim only to be willing to buy carbon fiber at or below $11/kg. Claims by carbon fiber suppliers have gone as far as to state carbon fibers could eventually reach $6.6/kg. Proof of carbon fiber production methods, which would enable such a low price, has yet to be seen. Conoco, has claimed that it can achieve the $11/kg with a plant producing 25,000kg annually – annual carbon fiber production volumes which would be required if a carbon fiber vehicle went into mass production. To-date, carbon fiber can still run as high as $40/kg, depending on the quantities purchased. As can be seen in Figure 11 of Chapter 4, to achieve cost parity with a glass BIW, carbon fiber price would have to drop to around $8/kg, and to beat steel BIW production costs, carbon fiber would have to reach nearly $5/kg. Assuming a carbon fiber market price of $11/kg can be achieved, the carbon composite BIW begins to appear a promising alternative. The work of the ACC has led to improvements in the design and processing of the carbon composite BIW, compared to the vehicle analyzed by Kang in 1998. These improvements have led to the carbon-composite BIW to go from being competitive with steel below annual production volumes of 19,000 to being competitive with steel below annual production volumes of 90,000. Across production volumes, the carbon fiber reinforced BIW is only approximately $100 more expensive than a glass-reinforced BIW – a cost premium that may eventually become feasible if the market valuation of vehicle light weighting, either for environmental or fuel economy reasons, rises. The impact of carbon fiber prices on the annual production volume at which steel-carbon cost parity is reached, is shown in Figure 33.

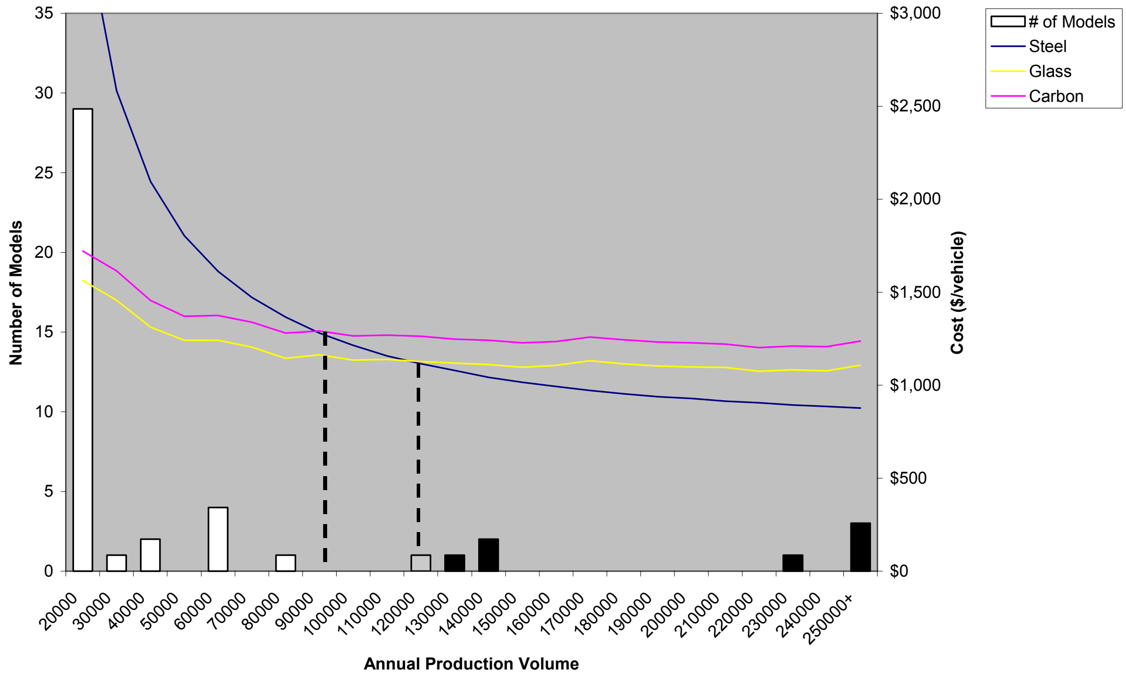
Figure 33: Sensitivity of Steel and Carbon Body-In-White Cost Parity Volumes to Carbon Fiber Price

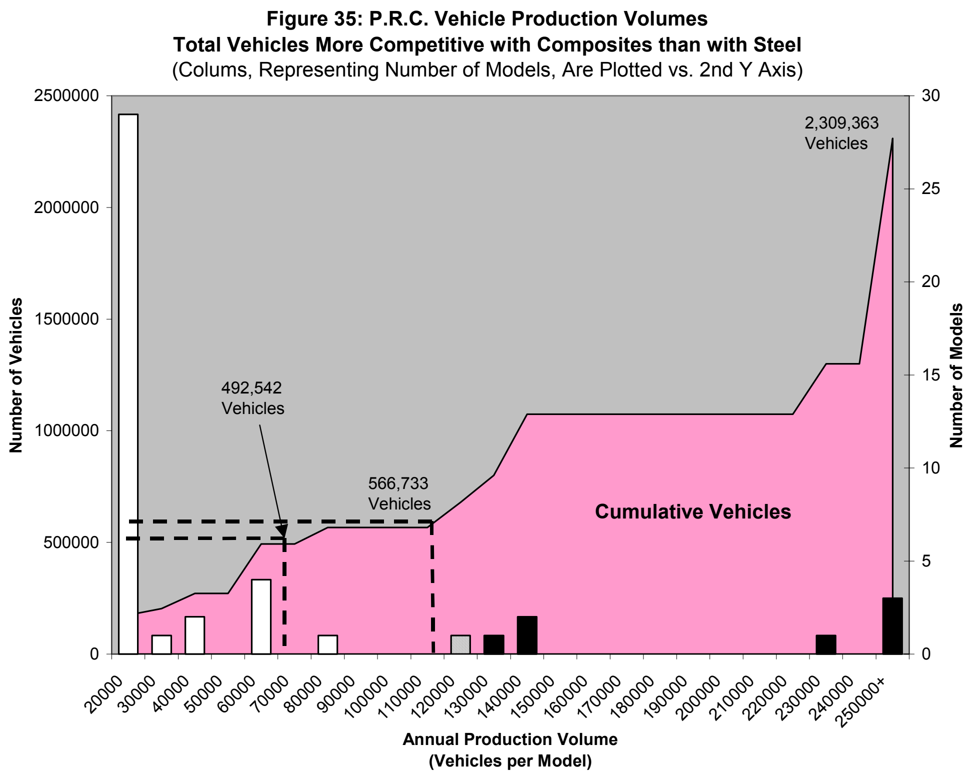


6.2. P.R.C. Discussion

Current plant production volumes for auto giants with ventures in China tend to be between 20,000 and 50,000 BIW units per year (Wang, GM Detroit 2002). Of the 19 foreign venture vehicle models produced in China between January and December of 2000, all of them had production volumes under 110,000, the glass composite's crossover with steel (CAC 2000). 79% of the models had production volumes under 65,000, carbon composite's crossover with steel (CAC 2000). Up through 10-20 years out, production volumes are not expected to go above 50,000 to 100,000 units annually (Wang, GM Detroit 2002), although plant capacity of, for example, the GM Shanghai plant, is 250,000 annual units (Steinfeld 2003). Given the assumptions of the two future scenarios, a composite glass BIW should remain more competitive than steel up to 75,000 to 80,000 units annually. Figures 34 and 35 present the distribution of 2000 production volumes for P.R.C. produced vehicle models alongside the original composite-steel cross-over points presented in Chapter 5 (Chapter 5, Figure 16).

Figure 34: P.R.C. Vehicle Production Volumes: Number of Models with Volumes Below Composite-Steel Cost Parity (Steel, Glass, Carbon Vehicle Costs plotted versus 2nd Y Axis)





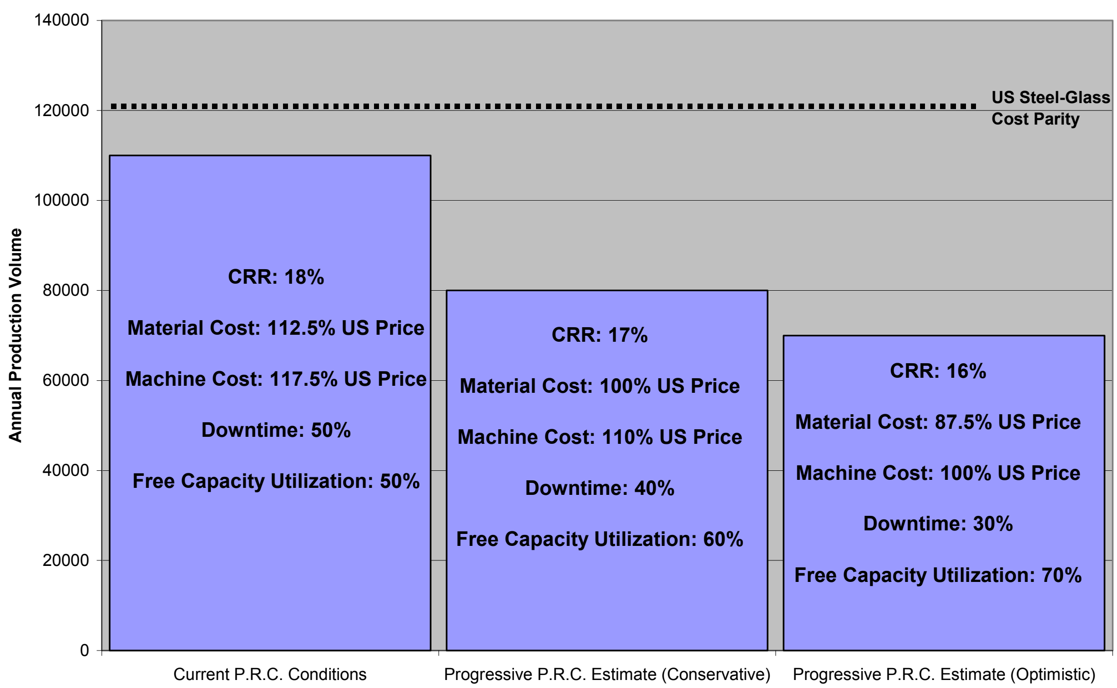
Given current and expected future production volumes, composites are and should remain less expensive than steel for production in the P.R.C. As can be seen by comparing the impact of varying utilization in Figures 26 and 27 versus its impact in Figure 28, composites also offer lower penalties for plant under-utilization. As such, the there is less financial risk associated with misestimating demand when choosing the capacity for which to build a plant producing composite BIWs than one producing steel BIWs. The benefit of lower risk in misestimating required plant capacities is particularly important in China where future production volumes are so unpredictable. The assembler industry and, even more so, the auto industry in China are extremely fragmented. Central leadership is aiming to consolidate the much fragmented auto sector, and nurture three major auto groups (ChinaOnline 2002). This consolidation of the industry would imply larger annual production volumes for remaining firms. In addition to not knowing the extent to which the Chinese government will follow through with consolidation efforts, it is difficult to predict the speed at which market demand will increase, the speed at which learning and skills will increase, and the speed at which factor inputs will change. Factors outside the country can also change the market demand plants within China are called upon to fill. The Asian Free Trade Agreement opens all of Asia for the first time to Chinese exports. The WTO opens China to unrestrained investment levels by foreign producers, who can use these plants to export throughout Asia. Still, both these internal and the external changes will take time. Assuming a plant fulfills its investment in 15 years, the production of glass-composite BIWs may remain the best option for multiple Asian car models for the immediate future.

In Figure 16 on P.R.C. BIW production and assembly, the steel curve is significantly flatter than in Figure 8, showing U.S. BIW production and assembly. The flatter P.R.C. steel cost curve creates a scenario in which there is little risk in choosing glass composite production over steel. At annual production volumes under 110,000, the production of the glass composite BIW is cheaper than steel – 10,000 yearly units less than in the U.S. However, if production volumes are above 110,000, glass composites only become at most $50 per BIW unit more expensive than steel. Due to composite's longer cycle times, plant capacities are significantly lower. Capital costs are also lower than in steel. As can be seen in Figure 26, at low production volumes, the difference between using 40% and using 90% of the free plant capacity is $190 for composites and $250 for steel. At high production volumes (250,000 APV), the difference between using 40% and 90% of the free plant capacity is still $150 for steel, while all capacity is already used in production for composites. On average across production volumes, the risk of losing money to low market demand and plant under utilization amounts to, a $30 per BIW difference for composites, but a $195 per unit difference for steel BIWs.

A Re-Assessment of P.R.C. Variable Assumptions

In evaluating the robustness of the results, it is important to step back and take a second look at the P.R.C.-specific assumptions. For ease of reference, the original variable assumptions and scenario implications are displayed again below (Chapter 5, Figure 21).

Figure 21: Sensitivity of P.R.C. Steel-Glass Cost Parity to Varying Assumptions



Capital Recovery Rate

For multinational firms, arguments differ on the most appropriate capital recovery rates. Using a capital recovery rate from the host country of a given production facility accounts for the risk associated with investment in that country. Using a capital recovery rate from the multinational's home country might be more representative of the actual cost to the corporation of spending the money (versus leaving it to accrue interest in the bank). Capital recovery rates cited for China range from 14% all the way up to 24% (Steinfeld 2003). The capital recovery rate in the United States is currently estimated at 12%. Similar capital recovery rate values could also be expected for the home countries of European automakers. A reasonable assumption when doing accounting for a foreign firm's manufacturing facilities in a host country is to choose a capital recovery rate somewhere between the rate at which capital could be acquired in the host country versus in the home country of the multinational.

In the results presented, capital recovery rates are 12% for the U.S. production facilities, 18% for current Chinese production facilities, and 17% and 16% for the conservative and optimistic future P.R.C. scenarios, respectively. The difference between a 20% capital recovery rate and a 12% capital recovery rate on the overall cost of a composite BIW is between $150 and $270 per BIW, depending on annual production volumes. The difference between a 20% capital recovery rate and a 12% capital recovery rate, is on average $290 per steel BIW. The impact of this 8% difference in capital recovery rates, however, can be as high as $600 at low annual production volumes (20,000). If the capital recovery rate in the P.R.C. is actually lower than assumed in this study, composites would be more competitive than currently depicted, with the largest impact at the lower end of production volumes. If capital recovery rates are, on the other hand underestimated in this study, although less likely, steel would become more competitive than depicted, both relative to composites as well as relative to steel production in the U.S.

Downtime

The impact of the possible scope of capital recovery rates on overall BIW P.R.C. production costs is, however, according to the assumption in this study, second to the impact of downtimes on those costs. On average across different production volumes, the difference between 30% downtime and 70% downtime amounts to a $490, $550, and $620 difference in cost, for carbon, glass, and steel, respectively. It is possible to argue that after the initial stages of learning in China, downtimes as high as 70% would not be likely. As downtime increases, it's impact on cost increases faster than in linear increments. If the range of downtimes were instead set from 30% to 60%, the difference in cost would amount only to on average (across different production volumes) $150, $170, and $200, for carbon, steel, and glass, respectively. At higher production volumes the cost impact is slightly higher and at lower production volumes, slightly lesser. Downtimes for production in the U.S. are modeled at 20%, and for production in the P.R.C. at 50%. Downtimes for the future P.R.C. production cost estimates are 40% and 30% for the conservative and optimistic assumption sets, respectively. If downtimes were higher than estimated, steel would be most greatly affected, followed by glass and then carbon. It seems, however, unlikely that downtimes would be so high as to cause the large cost impact seen at 70%. More likely is that downtimes are lower than currently estimated, which, given the non-linear increase in cost-impact with increasing downtimes, would actually not greatly lower the costs compared to the results found with the current numbers.

Material Price

Materials represent the largest contributor to costs for carbon and glass composite BIW designs, and the second largest contributor to steel BIW costs. Given this, it is important to reexamine the feasibility of the uniform material price mark-up applied to production in the P.R.C. In the P.R.C. assumptions, 12.5% is added to material prices to account for the material having to be imported to meet necessary quality standards. This uniform increase of 12.5% is not necessarily accurate. Depending on whether transportation costs are based on weight or volume, steel may actually have higher shipping costs than the composites, and glass fiber a higher shipping cost than carbon-fiber. This increase in cost according to weight, however, assumes that the steel, glass, and carbon would all be sourced from equidistant plants. This assumption of equidistant supply options is also not necessarily realistic. A combination of everything from small-scale to super-large integrated steel enterprises are already spread through China. China's demand for high value-added steel products, however, still greatly exceeds domestic capacity. A major policy goal has been to increase this high value supply. The local small-scale plants have made rapid progress in improving their high-end production capabilities. Likewise, there has been high-speed growth in the 20 steel enterprises (these 20 enterprises accounted for 62% of national steel output in 1997), especially in the four super-large integrated steel enterprises (Nolan 2001). It seems likely, therefore, that a close-proximity within country supply of steel may be available within the near future. Similarly for glass, in-roads have been made to create a glass fiber supply within China. Owens Corning already has over 100 facilities producing glass fiber in the P.R.C. Unlike steel and glass, the processes for carbon fiber are more sophisticated and less disseminated. Even assuming facilities able to produce carbon fibers of acceptable quality do eventually arise in China, like in the U.S., there would most likely only be a few plants with these skills and facilities. The likelihood of carbon fibers having to travel a greater distance than glass fibers or steel to automotive component plants seems high. An exception might be if the automotive component plants and the carbon fiber plants located or re-located into a cluster.

Even if a cluster were formed, transportation distances to either numerous assembly plants or to final sales locations would then in turn increase. It seems reasonable to assume that the carbon fiber would have at least the same mark-up as steel and glass fiber, if not higher, despite being lighter. Although glass fiber and resin are together lighter than steel, without further supply chain data, an equal mark-up also seems a reasonable assumption.

Machine Price

The difference between P.R.C. machine costs being 90% and 125% of the U.S. price, has very little impact on overall BIW costs. The cost-impact, despite this large a variation, is on average across production volumes, \$90, \$100, and \$195, for carbon, glass, and steel, respectively. It is unlikely in the near future that local technical skills will be sufficient to be able to source machines locally. The 17.5% (now), 10% (future conservative), and 0% (future optimistic) mark-ups, thereby seem reasonable. If anything, the 0% mark-up for the future optimistic scenario, is truly a bit optimistic.

Free Capacity Utilization

Utilization has even less of an impact on the costs of BIW production in China than machine mark-ups (except in the case of steel, where the impact of downtime and utilization are close to equal). Varying utilization between 40% to 90% impacts cost by, on average across production volumes, \$30, \$30, and \$190, for carbon, glass, and steel, respectively. Some evidence does exist suggesting free capacity utilization may be lower than 40% in plants. The GM plant in Shanghai has a annual production capacity of 250,000 units, however, currently only between

20,000 and 30,000 units are being produced out of the plant per year. These numbers suggest only 8 to 12% utilization of the plant. Further study would be required to observe the cost-impact of such extremely low plant utilization numbers.

6.3. Consequences for Global Issues: Emissions, Cross-Country Competitiveness, and Designing for Individual Regions

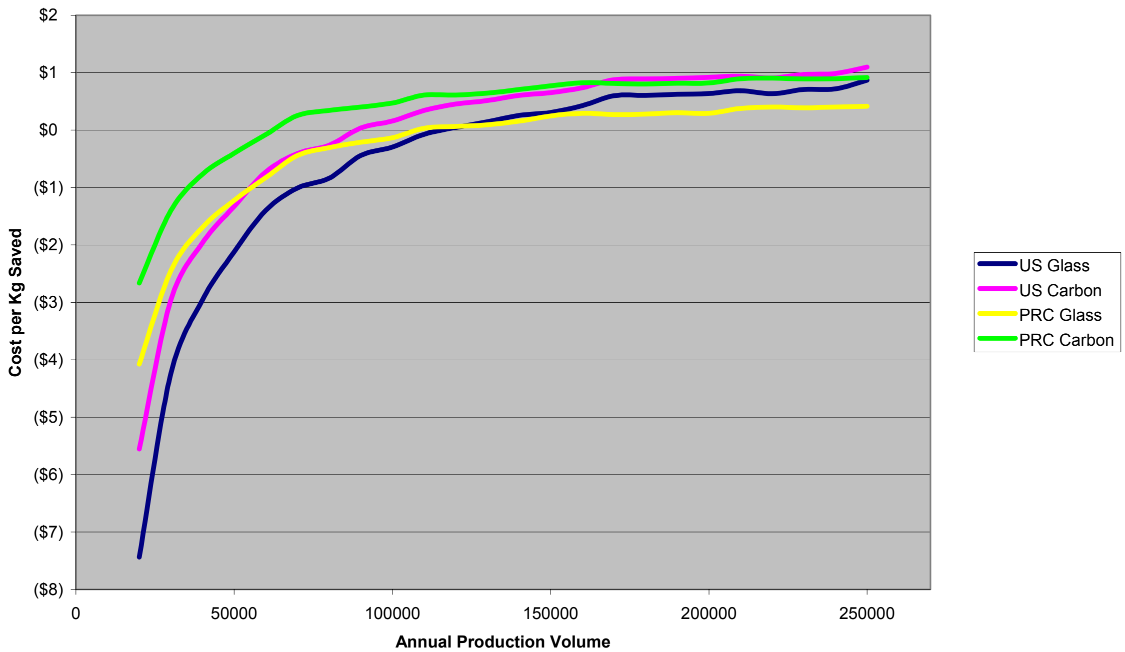
Design for Developing Regions

As discussed in Chapter 3, it is generally accepted that for developing nations, small-scale production using a relatively larger number of workers and less capital has more favorable production costs (Stewart 1990). This thesis work does not affirm this generally accepted assumption. Production of composite components requires more labor and less capital than the production of steel components (see Figure 15), however, composite components are less competitive against steel in China than they are in the U.S. Assembly of an all-steel BIW requires more labor and more capital equipment costs than assembly of an all-composite BIW. Overall, the production and assembly of an all-steel BIW requires more labor and more capital equipment costs than assembly of an all-composite BIW. In both the case of assembly and of the full vehicle production and assembly, carbon is less competitive in the P.R.C. against steel than it is in the U.S. To optimize the production costs of a design to a region, all inputs into cost must be considered: from where will materials, equipment, and tools be sourced to achieve necessary quality? How much will these sourcing decisions add or subtract from cost in comparison to the quality and reliability they will add or subtract? How large an impact does utilization versus downtimes versus capital recovery rate have on the particular process under developing world production assumptions? For the same process, replacing capital with labor may reduce that process's production costs in a developing country (depending on how much labor is actually needed versus how much the capital cost is reduced by the replacement); however, capital may not be the driving factor of cost, and much greater production cost reductions may be achievable through other means. When choosing between different processes, other inputs into each process's production costs may hold greater weight in the comparison than the fact that one process has higher labor content and lower investment costs.

Fuel Savings

Production cost is not the only factor worth considering during design for region. Not yet discussed, in this regard, is how much consumers might be willing to pay for light-weighting, or for durability, or other composite-specific characteristics. As an example, Figure 36 shows the cost per kilogram saved over steel for the composite designs in both regions. Cost per kg saved is defined as ($ composite BIW - $ steel BIW) / (steel curb weight – composite curb weight).

Figure 36: BIW Cost Per Kg Weight Saved
50% Secondary Weight Savings

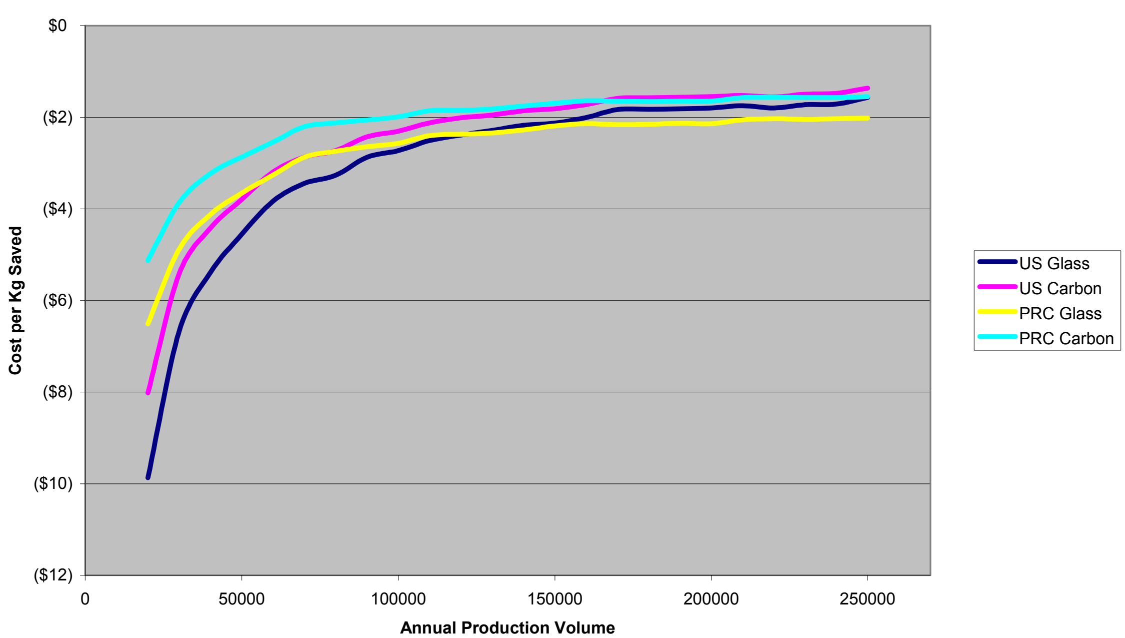


Weight saved in the BIW allows for additional weight savings in other areas of a conventional (gasoline-powered) vehicle, since less propulsion energy is necessary. These “secondary weight savings” on the vehicle curb weight are typically calculated at being between 40% and 60%. In other words, for every kilogram saved in the body in white, 0.4kg to 0.6kg are saved in the rest of the vehicle’s curb weight. Figure 30 and the subsequent calculations assume for every kilogram saved in the BIW, 0.5kg are saved in the rest of the composite vehicle.

Competing equations exist for determining the miles per gallon achievable at different curb weights. Applying the 5-10 rule of thumb (i.e. 5% increase in fuel economy per 10% reduction in weight) to a baseline 3111lb vehicle which gets 21.6 miles per gallon, leads to a relationship between fuel economy and mass of the following form: MPG = 895.24*(mass)-0.463. Using

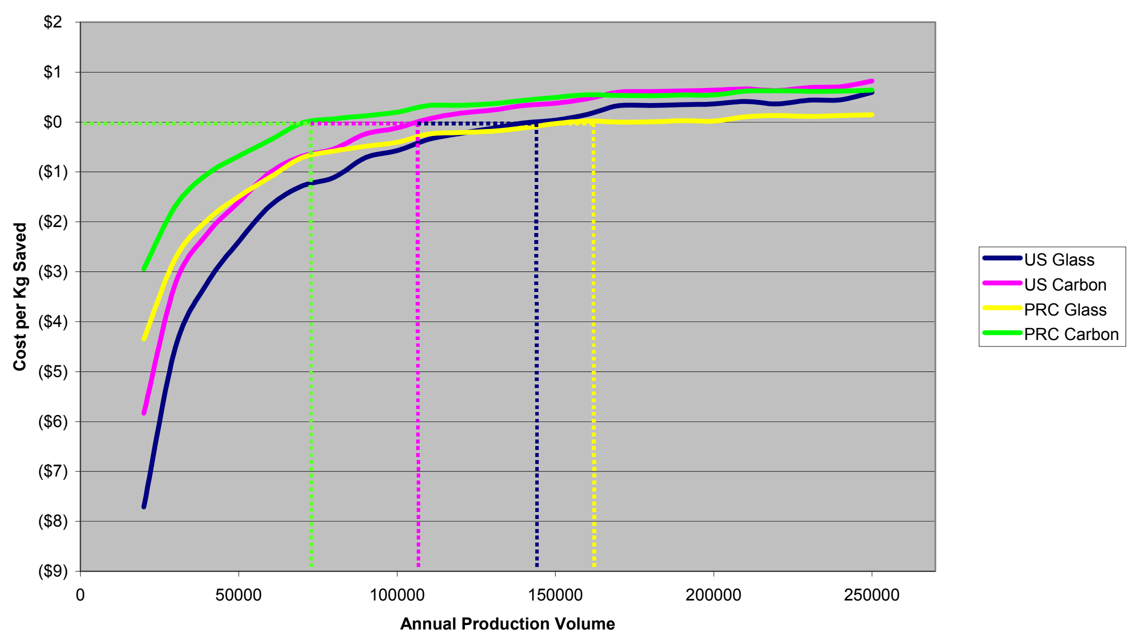
50% secondary weight savings and the 5-10 rule, the carbon composite BIW vehicle achieves 24.4 miles per gallon, and the glass fiber BIW vehicle 23.8 miles per gallon. In comparison, the steel vehicle achieves 21.6 miles per gallon. Assuming a vehicle drives 12,000 miles per year over a lifetime of 13 years, a vehicle can be estimated to drive 156,000 miles in a lifetime. If gas costs on average, $1.42/gallon, the carbon composite BIW vehicle would save $805 (discounted at 5%) over a lifetime, and the glass composite BIW vehicle, $645 (discounted at 5%), over the steel base case. Subtracting these lifetime fuel savings from the cost of the BIW, as can be seen in Figure 31, the composite bodies become more cost-effective to the consumer than a steel BIW. (These calculations assume the lower-weight non-body parts would cost the same as the equivalent, but heavier, parts had cost for the steel-bodied vehicle.)

Figure 37: BIW Cost Per Kg Weight Saved
50% Secondary Weight Savings
Lifetime Fuel Savings (@ 5% Discount Rate) Subtracted from BIW Cost



A different question is if consumers would see these benefits, and pay up to $360 extra in the case of carbon and up to $230 extra in the case of glass for an additional 2.8 or 2.2 miles per gallon in fuel economy, respectively. Most car manufacturers currently expect consumers to not look past the first year's worth of fuel savings when evaluating purchase price. Cost per kilogram saved over the steel base case when subtracting only the first year's worth of fuel savings is shown below in Figure 38. The U.S.-manufactured glass-reinforced BIW vehicle is more cost-effective than the steel base case below production volumes of 110,000 vehicles annually, and the carbon-reinforced BIW vehicle is more cost-effective than the steel base case below production volumes of 140,000 annually.

Figure 38: Body-In-White Cost Per Kg Saved Over Steel Base Case
50% Secondary Weight Savings
Fuel Savings Over 1 Years Subtracted from BIW Cost



The P.R.C. plots in Figures 36, 37, and 38, provide only a very rough estimate. In developing countries, longer driving distances can be expected in rural areas, and slower average speeds (and hence lower fuel economies) on both rural back roads as well as in the cities. Developing country vehicles can be expected to have significantly longer lifetimes. Numbers and calculations on these differences would be key to further discussion of Chinese and developing nation willingness to pay.

Emission Reductions

In addition to fuel economy benefits, consumers may eventually be willing to pay a higher price premium for reduced vehicle emissions. An initial look at energy saved per kilogram is performed by Frangi for both gasoline and alternative powertrains (Frangi 2001). This work suggests that a 35% reduction in BIW weight, such as achievable with a glass-reinforced instead of steel BIW, would lead to 10% energy savings. This energy savings can be directly translated to 10% savings in CO_2 emissions for gasoline powertrains. Frangi also looks the benefits vehicle lightweighting brings to enabling alternative power trains to achieve current-day vehicle performance target, which she estimates at 75W/kg. Given the assumptions in her work, Frangi shows that while a powertrain would require 110.11kW to achieve the current day performance target for a steel unibody, it would would require 96.66kW of power to achieve the target for a glass-composite bodied vehicle, and only 88.89kW to achieve the target for a carbon-composite BIW vehicle. Of particular interest for future work would be to understand the incremental costs associated with increasing the power of various powertrains, especially in adding leafs to the hydrogen fuel cell. An analysis could then be performed on the cost trade-off of reducing vehicle weight versus increasing the propulsion power of the powertrain. Further work on customer willingness to pay for miles per gallon savings and emissions savings (both in conventional gasoline powered as well as alternative vehicles) across regions would have key implications for composite feasibility in those regions.

Export Competitiveness

Another question is what potential exists for China to eventually take over production of automobiles, not only for its own markets, but for markets globally. Already many less complex products than the automobile are exported from China throughout the world. The comparison of each material's body-in-white costs in the U.S. versus China show cost of a composite BIW (both carbon and glass) produced in the U.S. to currently be significantly cheaper (~$200) than the cost to produce one in China (Figures 23 and 24). Cost of a steel BIW produced in the U.S. is cheaper than one produced in China at annual production volumes above 70,000 ($200 cheaper at 250,000 APV) (Figure 25). Looking into the future, however, production of a composite BIW in China has potential to be equal to or up to $200 cheaper than production of the same composite BIW in the U.S., depending on conservative versus optimistic future assumptions. For a steel body-in-white, using conservative future assumptions, P.R.C. production was $900 cheaper at the lowest production volumes and equal to U.S. costs at high production volumes. For optimistic assumptions, the steel BIW was between $1100 (APV 20,000) and $100 (APV 250,000) cheaper.

It is difficult to know without further study what the cost of logistics would be to ship components or full vehicles from the U.S. to China, from China to the U.S., or from China to elsewhere in the world. Veloso estimates logistics costs for shipping of subassemblies to be 8% of costs within the supply chain in a developed country, and 9% of costs within the supply chain in a developing country (4% and 6% of costs within the supply chain for shipping of components). The subassembly logistics cost values assume 2000km between customers and suppliers requiring two days travel time for a developed nation, and 500km between customer and supplier requiring one day travel time for a developing nation (the smaller supply distance and time in the developed nation assume local sourcing and a clustering of producers typical of developing nations). Using Veloso's cost estimates, this amounts to $49.29 in logistics costs for the BIW and $856.16 in logistics for a full vehicle in a developed nation. For a developing nation the logistics costs amount to $55.44 for the BIW, and $963.18 for the full vehicle. (Veloso 2001) A different set of information was available through World Transit Authority. For their composite-intensive vehicles, which have production volumes of 364 vehicles per year, sourcing of all materials into developing nations from developed ones (mostly from Japan for Asian developing nation manufacturing sites) amounts to $300 in additional costs per vehicle. (WTA 1999)

From the above logistics information, it seems reasonable to, as a first estimate, suggest that shipping components between the U.S. and China could add $50 in costs per body-in-white, shipping subassemblies or full body-in-whites between the U.S. and China $100 in costs per body-in-white. It seems unlikely that the optimistic future assumptions will be achieved in the near future. Going, therefore, with the conservative future scenario, it seems unlikely that China will become a global exporter of either composite or steel components, or BIWs. It does seem feasible that economies of scale and clustering of knowledge could lead to China producing for and exporting within the Asia region, even to Japan. Also, if an alternative vehicle emerges for developing nations, whether based on a design to cost-optimize factor inputs, a design tailored towards unique developing market needs, or a combination of the two, it would seem likely that China could hold an advantage in the production of this vehicle. This advantage could be both through knowledge gained in initial understanding of and production for its own market, as well as economies of scale benefits in later exporting to other developing markets. Further, China's location situates it centrally to much of the developing world, making it an idea nation to dominate alternative vehicle production and export.

7. Defining and Moving Towards Appropriate Technology

As first brought up in Chapter 1, technology decisions are inextractable from social and political ones. Technical (structural), economic (market), social (organizational), and political (stakeholder) forces all affect technology decisions. Likewise, the economic, social, and political well-being of firms, nations, and individuals are all in turn reliant in some way on those technical decisions. The technology most "appropriate" to promoting the well-being of a company, may or may not be equivalent to the technology choice most "appropriate" for the well being of a nation. Nor is the technology decision most "appropriate" to the well being of a nation necessarily most advantageous to the well being of the nations' individuals. As introduced in Chapter 1, theories on technology policy for both developed and developing nations often come down to valuation of the overlaps between corporate, national, and individual interests.

This chapter discusses policy implications of this work, first for the developed world example, the U.S., and then for the developing world case, the P.R.C., in three parts: (1) the role of cost versus other dynamic forces in driving the current levels of composites in each country, (2) what could be defined as the "appropriate" automotive body-in-white choice for a company, the nation, and the individual in each country, and (3) given these definitions, how can policy be used to move towards achieving more "appropriate" automotive body-in-white decisions in accordance with the policy goals set out in Chapter 1.

7.1 U.S. Policy

7.1.1. Dynamic Forces Driving BIW Decisions in the U.S.

The U.S. production cost results presented and analyzed in sections 5.1 and 5.3, and 6.1 and 6.3, respectively, provide new insights on the potential role of non production-cost forces. Assuming the cost results are correct, where technical decisions not production-cost-minimizing are chosen, it can be assumed that other dynamic forces are outweighing the significance of production costs. Four non-cost dynamics originally presented in Chapter 3, are revisited here: switching costs, uncertainty in design, public image, and the political influence of upstream technology.

As discussed in section 6.1, 67% of cars currently produced have annual production volumes at which having a BIW of carbon composite would be cheaper than having one of steel, and 78% of cars currently produced have annual production volumes at which having a BIW of glass composite would be less expensive than one of steel. Although composite BIW components have been implemented in some vehicles, they have not infiltrated vehicles on the market to the extent the above results suggest would be cost-optimal. If the potential for an even less expensive cost-optimizing BIW hybridizing composite and steel components is believed, even a greater percentage of vehicle BIWs on the market should, according to cost, include a proportion of composite components. Fuel savings over, alone, the first year of the composite vehicle's use bump the cost parity point of the composites with steel from at 90,000 to at 110,000 vehicles annually for carbon and from at 120,000 to at 140,000 vehicles annually for glass (Chapter 6, Figure 38).

A technical decision, which doesn't minimize production costs, may still be the most economical decision for the company. The auto industry has significant financial investment in the current technology – steel. A full understanding of the economic impact of technology choice on a firm would require comparing required equipment updating costs with the costs to revamp an existing plant onto a new system with the costs of building a new plant for the new technology elsewhere and selling off the old equipment, plant, and building space (in-house or to external buyers). Understanding the cost-impact of these alternatives would require further study. Depending on the impact of these switching costs, and consumer demand (willingness-to-pay) for light weighting, aluminum might be another BIW material alternative which would prove more competitive. A switch to aluminum would be able to use the existent steel plants, whereas composite production would require entirely new capital equipment investments. Depending on the significance of these switching costs, steel may remain more competitive than both composites and aluminum from a purely cost-to-company perspective.

Dynamic forces beyond company costs may be driving body-in-white decisions away from composites. A significant amount of risk and uncertainty still exists surrounding composite body design, production, and performance. Despite some experience with individual components in mass-produced vehicles, with mass production of a few specialty cars like the Corvette, and with hand-made racing vehicles, such as Formula 1 cars, composites lack the 30 years of design and mass-production experience associated with the usage of steel in body-in-whites. Although the properties of composites supply the potential for them to be stronger than steel, the strength of reinforced composite parts is design and processing sensitive, suggesting that crashworthiness will be difficult to predict for early designs. Likewise, early production is likely to run into unforeseen processing difficulties, low initial yields, and unexpected body malfunctions, possibly even requiring production run call-backs, later during vehicle use.

Beyond costs – production costs, switching costs, or costs associated risk such as necessity for additional redesign or product recall – demand, specifically here in the form of public perception of plastic vehicles, may also be play a large role in manufacturer's choice to steer away from composites even in instances where it provides production cost advantages. Manufacturers claim that there is a public perception of composites being "unsafe".[9] This public perception is perceived as coming from multiple angles. By being lighter weight, composites will be pushed greater distances in a collision than a heavier car. Due to their nature composites will frequently shatter in a crash instead of crunching, as typically occurs with a metal. Notably, neither the increased rebound distance in collision nor the shatter failure mechanism of a composite bodied vehicle would actually make it less safe. However, for marketing, it is perception, not reality, which matters. Along those lines, "plastic" is often associated with low performance, non-reinforced polymers by the general public, and not with the high strength, high stiffness properties found in structural composites.

Even if none of the above difficulties existed, historic evidence shows incumbent firms will, by nature, often resist technological change regardless of the benefits of the shift in technology would actually outweigh more immediate sacrifices. (Hart 2000)

[9] Arguably, this perception, if it exists, may have been created by advertising campaigns by the steel industry. It would also be imaginable that it could be overcome with marketing techniques, such as creating a catchy, high-tech name for the composite body-materials.

A final force likely to be playing a large role in inhibiting a greater change by the auto industry to composites is the political influence of the upstream industries for the automobile: namely, steel and petrochemical. The steel and petrochemical industries have significant interest invested in seeing the current automotive power train and materials systems remain in place. The combination of financial influence from powerful auto, steel, and petrochemical companies and electoral influence from labor dependent on these industries for their livelihood, creates a strong disincentive for elected officials to push environmental change. This constituency tied to the welfare of the auto, steel and petroleum industries creates a strong incentive for pork politics aimed at bolstering regional support and for immediate job and industry maintenance to take priority over environmentally progressive regulation which might arguably be of the greater long-term benefit to the constituents of their region.

7.1.2. Defining Appropriate U.S. Automotive BIW Technology

National, firm, and individual welfare are inextricably intertwined. A healthy national economy, among other features, has high levels of productivity. Individuals, capital, and material together produce goods. The production by firms, the resultant products, and the use or consumption of those products by consumers lead to environmental damage, which in turn affects the health of individuals, and their satisfaction with government oversight on their behalf. It is not attempted here to provide an answer to the optimal economic and environmental trade-off fitting to U.S. national interests nor to interests at the individual level within the U.S. Instead, the consequences and uncertainties surrounding composite application are revisited given the additional information now provided through the results, to provide greater transparency on the potential implications of different decisions. Further work would be required to begin to understand the magnitude of effect of different decisions, to weigh national versus individual versus firm interests given their interlocking nature, and to more sophisticatedly consider the weight of different social consequences – human health, versus safety, etc. Little in additional insights to the safety discussions in Chapter 3 were added by this study. Additional insights to the costs of air emission reductions, however, did emerge (discussed in Chapter 6).

The extent to which composite BIW technology hold promise for aiding long-term progress in environmental improvements is uncertain. On the side of solid waste, structural composites present difficult challenges to recycling. Life cycle analysis has been done on composites with differing results. Further work would be required to evaluate the indications of this work on full life cycle analyses. What follows focuses instead on what can more directly be gleaned – the cost-impact trade-offs indicated for emissions reductions.

The "appropriate" level of technical advance in composites, even when only considering vehicle emissions, is difficult to determine. Composites hold the potential for the reduction of gasoline and other non-hydrogen powertrain emissions through weight reduction of the overall vehicle. A gasoline-powered composite BIW has 10% fewer emissions than would occur with the same BIW in steel. Equivalently, a composite BIW requires 10% less power than a BIW of steel to achieve the same performance. Composite bodies thus also hold potential to enable the use of lower power density propulsion system. Currently alternative powertrains including electric vehicles, hybrids, solar, and fuel cells all struggle with achieving power densities sufficient to meet the performance and add-on requirements of U.S. consumers.

Hydrogen fuel cells provide a particularly interesting example both with regards to cost-power density as well as with cost-environment trade-offs. Theoretically, an optimum could exist at which the cost curve for lowering body and curb weight crosses the cost curve for increasing power through, for example, additional leafs in a fuel cell. This optimum would shift, as technological advances change the cost structures of both composite production as well as fuel cell production. Fuel cells are likely earlier on their technology s-curve (Fisher 1971) than composite body technology. Over time, therefore, the cost at which additional power can be achieved for the fuel cell will most likely decrease more quickly than the cost of reducing vehicle body weight through composites, allowing the same performance to be achieved with heavier vehicles.

For cost-environment trade-offs, the implications are equally uncertain and complex. Although lightweighting with powertrains other than hydrogen fuel cells decreases emissions, for hydrogen fuel cells, the only byproduct is water. Wide implementation of fuel cells does not, however, seem likely in the near future, continuing to leave composites in the running as a potential enablers of alternative powertrains and emission reductions short term. It is worth noting that, eventually, a steel BIW vehicle powered by a hydrogen fuel cell would both have zero emissions and could be over 85% recyclable. Wide implementation of hydrogen fuel cells is predicted to be achievable by 2010 by both the current U.S. administration and the auto manufacturers. Others sources estimate the full extent of this technology switch to be 20-30 years out. This far out in the future it could also be argued that there will have been advances enabling the recycling of composites, or that a new, lightweight, and recyclable material for BIW applications may have emerged.

7.1.3. Moving Toward Appropriate Automotive BIW Technology in the U.S.

Given the current understanding of composites in BIW applications, and their benefits, it seems advantageous for the policy to promote, at minimum, the implementation of composites for vehicles for whose production volumes a composite BIW would be more cost competitive than steel. This implementation of composites into the U.S. industrial and political environment may be achievable through a smart, “technology push” initiative from the government. The initiative would probably find the most support in conjunction with a comprehensive “environmentally sustainable private transportation” package. Such a package would require five iniatives: (1) to ensure the automotive industries that there will be no relaxing of new regulatory initiative, (2) to aid shifting of the steel and oil industries, (3) to aid re-situation of dislocated employees, (4) to consolidate efforts across industry stakeholders who would fall in favor of the regulation, and (5) to drum up support within the American people that such a move is necessary for both the economic well-being and security of the nation.

The first initiative (1), as is key to successful technology push regulation, provides regulatory certainty. Although the push nature of the regulation may not be welcomed, regulatory certainty is far preferable, often, to industry, than uncertainty, even if that certainty comes at a price of less favorable legislation. The second initiative (2) suggests helping the steel and oil industries “shift”. Ideally, such type of help would entail helping the oil and steel industries learn about and partially re-invest in upcoming industries requiring related skill sets. The third initiative (3) would ideally be achieved through creation of re-education program related to battery and fuel cell industries, and incentives for employees to enroll therein. The fourth (4) and fifth (5) initiatives are not easy to achieve. An alternative vehicle consortium has already been created through U.S. Car. As discussed, however, in Chapter 3, this consortium has arguably leveraged its power to add credibility to claims of what can't be done, rather than to accelerate advancement in these technologies. Technology forcing regulation with real deadlines and real consequences for not achieving, for example, a certain percentage of zero emission vehicles in the fleet and also a significantly lower across-fleet emissions average would give more meat to the meaning of the group. Even if the best people from each company were not sent to the consortium, it would act as a public forum for ideas, and companies themselves ensure they made advancements so as to remain competitive in the new regulatory environment. For passage of the legislation, to create a strong enough constituency across composite producers, battery producers, fuel cell researchers, and environmental groups will be more difficult. With a struggling economy, and security concerns in the middle east, however, a unique opening may come if the popular opinion swings against the war and the current administration, to find support for implementation of such a bill.

7.2. P.R.C. Policy

7.2.1. Dynamic Forces Driving BIW Decisions in the P.R.C.

The body-in-white P.R.C. production cost results presented and analyzed in Sections 5.2 and 5.3, and 6.2 and 6.3, respectively, provide new insights on the potential role of non-cost dynamic forces. Assuming the cost results are correct, when technical decisions are not production-cost-minimizing, it is assumed that other dynamic forces are outweighing the significance of production costs. Within the four theories presented at the end of Chapter 3, three – market demand differences, greenfield investment opportunities, and national interests – suggest dynamics other than production costs, which may be affecting the choice of composites versus steel in the P.R.C. Many similarities exist between the issues relevant to the P.R.C. and the switching costs, design uncertainties, public image, and the political influence of upstream technology issues discussed for the U.S. in 7.1.1. The consequences of these non-production-cost factors for BIW decisions in each country are, however, different.

As presented in section 6.2, 80% of new vehicles produced in China in 2002 would have been less expensive if they had been manufactured with a carbon composite BIW, and 82% of the new vehicles produced would have been less expensive if they had had a glass composite BIW. A vehicle cost-optimizing the use of composite and steel in its BIW may be able to be even cheaper. The choice to manufacture these vehicles with composite BIWs, is, however, not so simple. As China continues to progress, capital costs will carry less and less of a burden, and steel can be expected to become a more and more attractive alternative than composites even at production volumes as low as 75,000-80,000. In such future scenarios, the P.R.C. manufactured steel BIW becomes more cost-competitive than a steel BIW manufactured in the U.S.

The draw for the multinational to take composite BIW technology to China clearly goes beyond cost. For multinational firms, emerging markets, especially one such as China with one of the fastest growing vehicle markets and annual production of new vehicles already third largest in the world, provide a perfect place for learning and experimentation with emerging technologies. China provides a market where low cost is the bottom line in ensuring vehicle sales. It is expected for the market to accept the less attractive surface quality suffered even after painting composites, and even for the market to accept unpainted composite body surfaces. Likewise, gaps beyond the 2mm tolerances required in the developed markets to compete with Honda and Toyota typical of composites, are again not a concern in emerging markets beginning to find themselves with incomes high enough to consider purchasing a vehicle. Yet another concern of automakers with implementing composite bodies in first their world markets is lack of customer comfort with the different shatter mechanisms of composite bodies. Where as steel will buckle, when performing properly, composites will shatter when adsorbing the crash impact. While automakers fear first world consumers blaming any injury during a crash in a composite vehicle on poor impact performance, even if this is not true, emerging market consumers would not have these same pre-conceived notions of vehicle performance in crash.

As good as China's greenfield opportunities look to auto giants looking to test and learn with composite technologies, the opportunity to draw composite BIW technology may likewise be seen as an opportunity by the Chinese nation. National advancement in the auto industry could have spillover benefits throughout the industries within China. Learning done on composites can be passed into both Chinese military and aerospace applications, in which lack of this technology may currently be a bottleneck. As manufacturing using composites takes hold, Chinese firms and their laborers will develop tacit knowledge lacking elsewhere in the industry. Likewise, cluster theories suggest that with China already ahead of the rest of the world in attracting first attempts at mass-production of composite technology, there will be a tendency for more automakers and other members of the automotive value chain to also locate their composite BIW production in China. The more China is able to become a world-wide center of composite production, the more likely it is to be where the next generation of composite vehicle-body design and manufacturing innovations. With the high likelihood that composites will become the norm in autobodies 10 to 30 years in the future, China would be uniquely positioned to leapfrog the developed world into the future auto market.

7.2.2. Defining Appropriate P.R.C. Automotive BIW Technology

From a national perspective, the implications of using composite versus steel BIW technology in China differ with differing development theories. Theorists disagree over the pros and cons of open markets and free trade versus protectionist policies at different stages of development. For technology brought in by foreign multinationals, it is unclear to what extent the host countries will adsorb technology. Hypotheses range from adsorption occurring naturally versus significant industrial policy measures being required.

Implications for individuals versus nations under different levels of market isolation depend on the policies accompanying the choice. On the side of technology, development theories range from basic development with simple production methods aimed at local markets (Schumacher 1973), to catching-up in certain niches (Evans 1979) (Westphal 1985), to finding competitive space in the global market and leapfroging international competition (Brezis 1991) (Nonaka 2001) (Weiss 1989). While catch-up and leapfrogging theories imply the benefits of quicker national economic advancements trickling down to the individual (across what demographics depending thereby on economic distribution policies), the theories focusing on basic development with local production for local markets stress incremental development with incremental improvements in lifestyle for a broader range of the population.

Views of the "appropriate" balance of focus on social issues, such as individual safety and the environment, versus economic issues in developing countries also vary widely. In the case of these trade-offs, individual versus national implications depend on the importance placed by a nation's citizens on individual health and safety versus economic welfare, as well as the extent to which low economic welfare actually infringe on individual health. For a nation, key issues such as political stability versus instability and popular content versus discontent are inextricably linked with the economic well-being and the environment and safety of its citizens. In addressing "appropriate" BIW material decisions for the P.R.C., it is not attempted to support one theory or another or to choose between trade-offs discussed. The consequences, as suggested by the different theories, of choosing composites versus steel technology are discussed.

For BIW technology, China, as a nation, has the option to accentuate the manufacturing of composite BIWs within its boundaries, to let the market decide, or to hedge its bets by making sure it has steel BIW production capabilities at the same time as allowing some firms to move forward with composites. On the upside, China may gain important technical expertise, more emissions-friendly vehicles, and the opportunity to come out ahead of the developed world when and if composite technology becomes the primary paradigm for vehicle bodies. On the down side, extensive employment and economic benefits come to China from its steel industry. China may or may not find similar success in the composites industry and with composite production. China risks failing to catch-up in BIW design with steel by extending resources and energy towards composite BIW production. China also risks the resources put towards composites being wasted time and energy all-together both if composite BIWs do not become prominent in the future automotive market, as well as if China finds itself unable to become competitive for technological advancement or other reasons in composite design and production.

Uncertainty abounds in whether the ups or the downs of a venture in composites would win out. Further, the benefits listed in the ups are different than those listed in the downs. This difference in benefits suggests different decisions depending on China's weighting of environmental versus economic factors, as well as the weight given to the impact on the individual (versus the nation as a whole). While basic development theories might lean towards developing composites or steel according to which fits better to the local market (both in the sense of production cost and demand), catch-up and leap-frog theories would suggest going with the material alternative more likely to make China competitive in the global market. If China were to orient itself primarily towards the global market, it is important to make note that the factor inputs available in China actually made composites less competitive against steel than they were in the U.S. Thus, if focusing on composites, China would be placing its bets on, given lack of experience internationally on composites, being able to learn faster since regional factors on their own don't lead to lower costs.

Uniquely, composite BIWs fit both current demand characteristics in China as well as have long-term promise for the global marketplace. They appear an attractive alternative according to both basic development theories as well as leapfrog development theories. Composite BIW production causes the greatest concern for the catch-up theory. The consequence of the catch-up development theories proving most suited to China are that the decision to produce composites would leave China hit from both sides – it would find itself unable to successful design and produce BIWs out of composites (a danger also possible given the basic development theories), and, after investing, it finds there to be no global market (a risk also taken when making leapfrogging attempts). One policy option both fitting with China's ideology and fitting with China's display to date of willingness for experimentation might be hedging its bets by encouraging both steel BIW and composite BIW production. The implementation of such a policy is discussed in section 7.2.3.

If China does act to encourage the implementation of composites, the role it should play in protecting the safety of its people as laborers in the industry and final vehicle users is a complicated question. Composites are a risk on many levels – for production worker safety, for user safety, and for firm economic success. Composite may, on the other hand, hold significant environmental and economic rewards for the Chinese nation. If realized, these environmental and economic benefits would benefit the Chinese people. The sections and magnitude of the population reaping the majority of these environmental and economic benefits would vary depending on policy. The labor requirements of plants would benefit employment in the regions they locate, however labor in steel industries may as a consequence suffer.

The safety of associated Chinese labor and vehicle users given the implementation of composites is important to consider. In the U.S., extensive regulation protects worker safety. For composite production, this includes protecting workers from resin and adhesive fumes and protecting workers from inhalation of reinforcement fibers, in addition to protection applicable more generally to production including protection against high risk of injury from working machines, from ancillary shop floor equipment, from repetitive strain or poor ergonomics, or from heavy lifting. Without further study, it is difficult to assess if the risks posed to Chinese workers on composites without developing nation worker safety regulations in place are higher than these workers would be subjected to in the production of steel BIWs. Users of composite vehicles would most likely be subjected to higher risks, as early prototypes work towards perfecting the technology. Likewise, private vehicle owners and small repair shop owners will most likely not have protection or be warned against the dangers of fiber inhalation and chemicals and vapors in the resins and adhesives during maintenance. Ideally, such preventable risks should not have to be borne by the Chinese people. However, the environment takes a back seat to economic advancement at all levels of the Chinese society. It seems likely any vehicle and any job (especially for the 30% of Chinese citizens below the poverty line and the 120 million unemployed (UNCHINA 2001)), regardless of how safe, will be seen as better than no vehicle and no job.

7.2.3. Moving Toward Appropriate Automotive BIW Technology in the P.R.C..

Given its potential for cost advantages for steel BIW production in the future, and also given the uncertainty as to composites' role in future developed and developing nation vehicle markets, the wisest option for China may to hedge its bets by continuing production and advancement in steel BIWs but allowing foreign and supporting equal levels of local experimentation in composites. The following section discusses the choices involved in implementation of such an approach.

It will be important for China to consider its approach towards national vehicle producers versus joint venture manufacturers and foreign direct investment. The strong role of foreign direct investment in driving China's development is unique among developing nations. All of the western auto giants, as well as Honda and Toyota, currently have joint ventures with a foothold in the Chinese market with steel BIW vehicles. Although China has many forms of protecting its own firma and interests, foreigners frequently control the transfer and advancement of technology. China's flexibility with regulation and with avoiding holding to a single industrial policy stance, however, has created an atmosphere where experimentation is welcome and in which multiple directions can be taken at once.

Thus, fitting with much of China's industrial policy would be for China to welcome foreign ventures to experiment with composite BIW production as they find feasible for local demand or pure technological experimentation reasons. In this manner, China can gain experience in composites, but avoid putting themselves at overly high risk to unsuccessful composite production experiences or future auto markets turning away from composites BIWs. By encouraging experimentation with composites as naturally occurs in the market, China also runs less up against the problem of competing with steel and petroleum interests, or employment and local economy concerns that would arise from loss of market within those industries.

Encouraging foreign companies to experiment with composites in-country is, according to proponents of the importance of local expertise for foreign transferred technology to be adsorbed, not enough for the China to gain from those operations. To achieve adsorption of transferred technologies, it is likely important for China to involve its own companies, universities, and R&D institutes in composite material production, composite automotive BIW design, and composite automotive BIW production.

China's reinforced plastics industry is the potential supplier for auto manufacturers in China pursuing composite BIW designs. Already, China's reinforced plastics industry is one of the fastest growing industries in China due to soaring demand from end use markets including construction, automobiles, plastic pipes, electrical, and electronics (AsiaMarket 2001). Automotive reinforced plastic consumption is expected to grow 10.3% annually between now and 2005 (AsiaMarket 2001). Building up local Chinese resin manufacturers, fiber manufacturers, and component manufacturers would help the nation be able to take advantage of this growing market as well as of developments in composite BIW production and design. Many precedents exist that China takes an interest in building up local skills and expertise around technology it is interested in transferring, whether for national pride or actual technology adsorption reasons. Examples related to the auto industry include its interest in having its own national auto manufacturer, and its building up of electric and fuel cell capacities in universities and R&D centers to coincide with local experiments in these technologies and international interest in experimenting in China with these technologies.

Downstream of supply, China is also building up local expertise. China continues to work towards developing a national auto manufacture, and, correspondingly, to consolidate its national vehicle industry into three key players in automobile manufacturing. The Chinese Huatong Motors venture with designer *Automotive Design* (the venture is called the Sinoamerican Motor Corp. and is located in Deyang, China), became the first mass producer of composite BIW vehicles world-wide. (RMI 2002). Huatong Motors, however, is not one of China's three targeted vehicle companies. (Nolan 2001). In conjunction with its consolidation efforts, China could either encourage one of its three targeted vehicle companies to take-on and expand

Huatong Motors production and development efforts, or encourage all three to have subsidiaries with composite body efforts. Given the desire by company heads for national recognition, having one of the three targeted vehicle companies take on and then focus solely on the composite body vehicle, might lead to greater efforts on the composite vehicle, since the company's national recognition would depend on the composite vehicle being successful, and the company could not fall back on the success of its steel models. On the other hand, having each target vehicle company have a composite vehicle subsidiary or division would encourage a greater flow of knowledge between the lessons learned in metal body production and the lessons learned in the composite body production. An additional advantage comes from the fact that although China has made efforts, in line with its national auto goals, to consolidate the auto industry, it still allows new small auto manufacturers oriented towards local lowest-level markets spring up. If they see composite body designs as most profitable given costs and market demand, these small ventures will go for such designs, and lead to further learning at the micro level.

By the having local companies and institutions themselves being invested in composites, China increases the likelihood that full learning will take place to the point that China can eventually take the technology forward on its own, and break free from the position of being continually dependent on the brains and technology transfer occurring within the joint ventures. Through this involvement China opens up the door both to taking over the higher level management and R&D jobs within the foreign join ventures, and to being able to take advantage of employee learning within these joint ventures by later attracting these employees into the Chinese firms. In addition to aiding technology adsorption, Chinese investment in the universities and infrastructure would provide foreign auto manufacturers tangible assurance of China's commitment to developing a resource of labors skilled in composites design and manufacturing as well as to providing the necessary infrastructure to help production of composite body vehicles in China be a success.

So long as the vehicles manufactured in China are for Chinese consumption and not for export, it is less likely activists will be able to successfully put pressure on multinationals to take responsibility for job and vehicle safety in association with composite vehicle bodies. Likewise, so long as the Chinese government believes there is the risk of losing investment by increasing safety regulation stringency, it will not happen. The best hope for protection of Chinese laborer safety associated with composite vehicle production would be the invention of low-cost mechanisms to enhance worker safety from within the associated government agency, from within academia, preferably with government support, or out of simple human concern from a foreign top manager within the joint venture. With regards to composite BIW vehicle user safety, the largest driver will most likely have to be the industry's own desire to improve crashworthiness so as to enable the technology's implementation in developed markets.

7.3. Manufacturing Costs and Regional Design

In drawing implications from this thesis on the role regional factor inputs should be playing in product and process design decisions, it is instructive to break the discussion into three separate scenarios: (1) from a perspective of manufacturing costs, is it important to consider region in design, (2) from a perspective of manufacturing cost, are there generalizable rules which should be followed during design for emerging market regions, and (3) would these rules change if the domain were changed to consider not only manufacturing costs but also local social welfare. This section looks at the previous conclusions in the literature on each of these three issues, in light of the composite BIW production results for the U.S. versus China. A generalizable approach is then sought for (1), (2), and (3).

Appropriate technology and technology choice literature suggest a need to consider regional factor inputs in product design and manufacturing decisions in developing countries. This literature is aimed at achieving what Schumacher coined "enlightened" social and economic development in poor and rural regions of developing countries. Although later literature suggests that "suitable technology" as defined by Schumacher may in some cases be more, rather than less efficient, economic feasibility was not the focus of the movement. Economic advantages to at minimum three of Schumacher's four criteria for "suitable technology" – low capital costs, low economies of scale, and low skill requirement – can easily be imagined for production in developing regions. Low capital costs and labor-intensive production is generally accepted by multinational firms as the economically desirable process goal for production in developing countries. Work has also been done on the limited benefits of economies of scale, especially in rural regions, when transport factors are taken into account (Jackson 1972); (For a more general discussion of the limits to economies of scale see (Stein 1974), (Sale 1980) and (Krugman 1995).) Academic analysis of the most cost-effective manufacturing procedures for developing regions has been limited.

The results of this thesis suggest that the impact of regional factor inputs on manufacturing costs encourage regional specialization in auto body-in-whites. Alone differences in regional factor inputs cause different body-in-white solutions to minimize production costs in the U.S. versus in China. These results suggest that region, from a perspective not only of market, but also of factor inputs, should be considered in the development of automotive body-in-whites for China. China is an emerging market, while the U.S. is a developed one. Although the characteristics demanded of automobile body-in-whites varies decently between countries, further study would be required to determine if the impact on manufacturing costs of variance in factor inputs across developed and, separately, across developing regions, is significant enough to warrant distinguishing between individual regions, or only between developing regions versus developed ones. It seems likely that cost-impact of variances in factor inputs across the developing regions would warrant further distinguishing between types of regions. For example, it may be necessary to have a different design approach to developing regions with large and changing indigenous markets like India, China, and Brazil, and developing regions with more impoverished populations such as Africa. It likewise may be important to distinguish between isolated regions within developing nations due to lack of infrastructure, and more connected and accessible regions within those developing nations.

In the case of the automotive BIW, increasing labor intensity and decreasing capital costs were not the most significant factors for lowering overall manufacturing costs in China *with the given process*. The single largest impact on cost for the composite BIWs was material, followed in a distant second place by capital. For the steel BIW, the largest cost was capital, followed closely then by material costs. Given the feasible magnitudes, by which the factors affecting manufacturing costs could be varied, downtimes had by far the largest impact on all both steel and composite BIWs, followed by capital recovery rates – a variable which would only be changeable within the country over time. Notably, these results are specifically for what was perceived of as the boundaries of the process modeled. Some recent evidence does suggest that capital costs could be lowered by more than varied in the analysis, and labor intensity in exchange increase. If these changes are true, both capital recovery rates and downtime could be expected to have a lower impact on overall costs. Likewise, it is difficult to foresee how different, small-scale process designed specifically to developing region characteristics might be able to compete.

The results of this thesis neither encourage nor discourage labor-intensive, low-capital, small-scale technologies for developing countries. The low-prominence of labor in the results of Chapter 5 suggests that low labor costs would not be a good reason for moving BIW production to a developing nation if the focus is export-oriented production. For production for the local market, a developing world designed for higher labor-intensity and lower capital intensity should have lower costs than if the developed world technology were transferred as is. This phenomenon ceases to be true at the limit at which costs of quality problems due to natural human error as well as less experienced labor force outweigh savings from decreased capital. Due to quality concerns, whether or not to use local materials is likewise complicated. The lower price and transportation costs of local materials must be weighed against the cost of lower quality.

Choosing appropriate economies of scale for a production facility is complicated. The greater the isolation of the region, the more cost-competitive a process would be with small economies of scale, due to prohibitive transportation costs. Depending on infrastructure surrounding the production site, technologies with high efficiencies at low production scales could prove at a large advantage over processes requiring large economies of scale and significant transportation of final products. The magnitude of transportation costs to and from the site can also drastically increase the appeal of local materials. The results in Chapter 5 assume a relatively accessible plant such as GM's Shanghai venture, and are not address the full range of issues for production, in rural China. The capital intensity associated with production of the incumbent technology in the developed world will also impact the scale chosen for plants. The less capitally-intensive the state-of-the art, the greater the immediate feasibility of plants with small economies of scale.

The results presented in this thesis provide insights into product and process decisions for the production of a BIW in typical plant site in China. To extrapolate from these results to other industries is, however, difficult. Unlike suggested by Willoughby, the importance of increases in scale of production to overall efficiency in developing regions is extremely technology dependent, and can most likely not be generalized across industries. The extent to which the importance of economies of scale for a product and its production process can be changed to fit regional factors would most likely vary greatly with the product and its technology. A generalizable set of questions to address in optimizing the cost-competitiveness of a technology to be manufactured in a developing country do, however, seem to be derivable:

1. How large, geographically, is the market you are considering serving out of your manufacturing plant.
2. What competition, if any, exists from other companies and or technologies for the market you are considering.
3. What is the level of isolation for the market you would be serving. Would this isolation suggest advantages to small economies of scale with local materials due to prohibitive transportation costs?
4. What is the cost structure of your process. What range of changes could be expected in these costs? Would these changes be significant enough to warrant addressing? Along what dimensions can this cost structure be changed to better meet the conditions suggested in your answers to 2. and 3.?

Suggesting parameters for product and process design to considering not only manufacturing costs but also maximizing social welfare, requires agreement on both on the unit of analysis – individual, firm, or nation – as well on what physical actions actually lead to desired social welfare goals. Using the regional production cost analysis methods developed in this thesis to be able to add actual process and cost implications to the debates on basic versus catch-up versus leapfrog development strategies is a fascinating direction to take future work.

8. Conclusions and Future Work

8.1 Conclusions

In the problem statement in Chapter 2, it is asked what forces are leading to the current levels of structural composite interest and application in the U.S. vs. China. In the U.S., composites appear to be applied at lower rates than optimal according to manufacturing costs, while in China, interest in composites is significantly greater, despite for a larger percentage of the vehicles long-term manufacturing cost estimates not being as clearly favorable for composites over steel. A portion of this difference between composite application in the U.S. and China can be explained by market differences between the two countries. Concerns of tolerances, outer body panel surface appearance, additional safety precautions during processing, and legal ramifications of different or poor understanding of failure mechanisms during crashes do not hold the same weight in China as they do in the U.S. Likewise significant is the greenfield investment opportunities in China, versus the embedded capital costs and stakeholder interests associated with steel in the U.S. Although the U.S. has promoted some composite technology initiatives, such as the ACC, the financial influence of the large corporate auto, steel, and oil stakeholders and the electoral influence of the large population whose employment depends on these issues is likely to be preventing high-impact government intervention. National incentives may exist for the Chinese government to encourage investment in composites, however, if any actual steps in this direction are being taken by China, as well the incentives and influence of stakeholders at the micro-level for or against composite introduction, is unclear.

Market demand for environmentally friendly transportation is growing internationally, both through regulatory and popular trends. At the same time, the social costs are growing of the impact of automotive emissions on the U.S. people. Both of these trends suggest that it would be economically and socially beneficial for the U.S. government to encourage emission-reducing initiatives, including more extensive implementation of composites in automotive body-in-whites. An increase in composite introduction in the U.S. would be difficult to achieve. A successful initiative would at minimum require technology-push regulation in conjunction with ensuring industry certainty of enforcement and follow-through; industry aid to the steel and oil industries in a shifting of investment strategies towards initiatives associated with the composite and alternative powertrain technologies; re-education aid to constituencies employed by the auto, steel, and petroleum industries towards skills associated with production and engineering of composite and alternative powertrain technologies; consolidation of stakeholder lobbying efforts who would be in favor of the infiltration of these technologies; and a raising of the level of popular push for such initiatives.

Most advantageous to China from an economic standpoint would likely be to hedge its bets between composite and steel BIW technology. By encouraging both foreign ventures as well as local firms to experiment with mass composite BIW vehicle production, China opens itself to the opportunity to leapfrog the developed world in future automotive body production. The early introduction of composite bodies also provides environmental benefits, by reducing what is quickly becoming the largest contributor to China's growing and dire air pollution problem. Advances in composites further have benefits to Chinese national security, both through reducing oil dependency as well as in increasing necessary knowledge for aerospace and high-tech military applications. By maintaining some foreign and local ventures in steel, however, China provides itself, economically, with the required knowledge base if steel bodies with alternative powertrains end up being the direction taken for BIW technology in the future. Overall, however, encouragement of investment in composite BIW production should not be approached tentatively for fear of insignificant hedging with steel production knowledge. The interest of foreign ventures in producing composite BIWs in China provide an incredible opportunity for China to gain tacit production and design development knowledge to give it first-mover advantages in a technology likely to be a key foundation not only in automotive but also in many other applications in the future. Given the unique role the Chinese government is able to play in its market economy, China is in a position to truly have a positive impact on the initiative undertaken by local and foreign automotive industries with composites in BIWs. China's greatest two challenges in this undertaking will be creating the infrastructure in inland and western China necessary to create feasibility of investment also in these regions, and balancing the labor, usage, and environmental safety interests of its people against the priority placed on economic advancement above and beyond personal welfare by all levels of society.

The role regional factor inputs should play in product and process design decisions is best broken into three scenarios: (1) the importance of region, generally, in design from the perspective of manufacturing costs, (2) differences in this approach when dealing with developed versus developing country regions, and (3) differences in this approach when social welfare considerations are added to the decision framework. The results of the thesis provide insights into scenario (1). These insights suggest that the impact of regional factor inputs on manufacturing costs encourage regional differentiation in automotive body-in-whites at minimum between developed and developing countries, and not a homogenous body-in-white design. A focus on increasing labor, decreasing capital intensity, and encouraging simplicity, as suggested for social reasons by appropriate technology proponents, does appear that it would, in the case of body-in-white production, help with the sensitivity of the process costs both to capital recovery rates and downtimes. Although the cost-optimal ratios of labor and capital would definitely be different in developed versus developing countries, it is not clear that this focus would have an equally significant cost-impact on all products processes. Likewise, the focus on use of local materials presents a price-transportation-quality trade-off, where the optimal cost solution will vary by product and process. The manufacturing cost-benefits of focusing on low-scale production suggested by socially concerned appropriate technology literature is likewise difficult to generalize across technologies. For example, composites reach economies of scale at much lower production volumes than steel, but are actually less cost-competitive against steel for manufacturing in China than for manufacturing in the U.S. The most cost-effective production scale will, as a function of transportation costs, local material quality, and the process-inherent economies of scale, be most directly dependent on the isolation of the manufacturing region.

Some consideration towards optimizing cost-competitiveness of manufacture in a developing country do, however, seem generalizable across regions and industries:

1. How large, geographically, is the market you are considering serving.
2. What competition, if any, exists from other companies or technologies for this market.
3. How isolated are the individual markets you are serving. What does the combination of the level of isolation and your process cost-structure suggest for local versus more centralized production.
4. What is the cost structure of your process, and what dimensional flexibility can be expected from the individual variables making up this structure.

8.2 Future Work

Technical Alternatives

As discussed in section 4.4.2.3, several technical alternatives are not covered in the three-case comparison provided in this analysis. The cost-performance benefits of alternative materials such as aluminum and thermoplastic instead of thermoset resins, of alternative processes such as SMC and RTM, of alternative designs such as space frames, and of outside-the-limits production volumes such as below 20,000 or above 250,000 vehicles annually, would all be of interest to pursue.

Cost-optimizing Material Hybrid BIWs

As suggested by Kang, depending on the unit of analysis, one useful BIW solution may be a hybrid of composite and steel components. Foci for this hybrid approach could include minimizing production costs willingness to pay for fuel economy or emissions reductions, minimizing repair costs, making sure the end-of-life vehicle meets profitability requirements to be sought-after by shredders and dismantlers, or maximizing the vehicle's score in life cycle analysis. To further pursue the role of regional factor inputs in BIW process and design decisions, it would be instructive to determine if and how the cost-optimized solutions differ for the U.S. versus China across the production volume range already studied. Further work to enable a more sophisticated analysis incorporating the impact of platform sharing across models would be additionally instructive for real-world application. It would likewise be instructive to add additional country "scenarios" to the analysis to suggest what level of regional differentiation for these analyses ceases to be useful in providing insights on cost-significant differences in design. (For example, is developed versus developing regions a sufficient breakdown? Is developed, developing, and least developed, as defined by the U.N., a more instructive categorization of the factor inputs structures common to different regions? Or, is even further categorization of regions beneficial when attempting to cost-optimize designs? Note: The cost benefits of platform sharing from a development perspective is not incorporated here and would require separate analysis.)

Cost-Region-Environment Analyses

Three additional environment-cost analyses, performed separately for the U.S. versus China, would be particularly instructive for body-in-white decisions in each country. First, it would be instructive to perform a more complete analysis of the impact of body lightweighting on vehicle emissions incorporating differences in typical percentages of urban versus highway driving and also differences in typical urban versus highway speeds between the two countries. Secondly, additional study of alternative powertrain production costs, especially for fuel cells, may provide the opportunity for cost-optimization between body-lightweighting versus increase in powertrain propulsion energy. Thirdly, differences between social costs currently caused by environmental damage in each country as well as differences in value of life estimations may lead to significantly different cost-benefit analyses of the installation of different environmental measures in each country. Although these cost benefit analyses, no less value of life estimations, are highly disputable, they could be instructive as a departure point for issue discussion.

Impact of Logistics

Significant amounts of sophistication continue to be desired in the current analysis's approach to logistic and supply chain factors. Most immediately instructive would be further research on the contribution of logistics to overall costs of the automotive body, as well as of the final automobile. Five factors would be particularly instructive in improving the current analysis's incorporation of supply chain costs: incorporation of inventory costs, incorporation of transportation costs, incorporation of regional isolation/infrastructure considerations, incorporation of isolation-transportation-quality-scale trade-offs in location decisions, and constraints to better define and incorporate product and value-chain import-export decisions.

Applicability and Limits of Modeling Approach for Exploring of Alternative Product and Process Design Concepts

This thesis models the cost-impact of U.S. versus China factor inputs for accepted steel and composite BIW production techniques within a given sensitivity range. More recent research has begun to explore increases in labor intensity in exchange for decreases in capital for developing country environments. Without further knowledge about the process alterations being considered, it is difficult to estimate the extent to which sensitivities on the current model would be able to represent the associated cost structure which could be expected to emerge. Running variable sensitivities definitely provide insights into the weakness of the modeled process, for example, for the focus of this thesis, in addressing the factor input structure of a given region. The extent to which such sensitivities can provide insight beyond areas for improvements of the incumbent process towards an alternative more technology more appropriate to the factor inputs of the region is difficult to evaluate. Extensive insights might be gained in this regard through more extensive interactions between model designers and product and process innovators and engineers.

Greenfield-Brownfield Quantification

The materials systems lab process-based cost models current do not have an approach to quantitatively incorporating how cost-optimal product and process design decisions may differ for greenfield versus brownfield production facilities. Addition of this capacity to the models would be instructive for choosing when to make incremental plant improvement; for when to opt build entirely new production facilities; as well as for choosing whether, how, and where to adopt and implement emerging technologies.

Policy Development

The assessment of policy alternatives provided in the thesis is extremely cursory. A more comprehensive approach would be required to engineer actual, implementable policy in either nation – the U.S. or China. Such an approach would require greater study and empirical data collection on stakeholders, incentive structures, and power structures in each nation, as well as a look at international organizations and interest groups and their potential impact and role.

Leapfrog Potential for China in Alternative Powertrains

Research during this study ended up stumbling across the potential for China to leapfrog the developed world not only in composite BIWs, but also in alternative powertrain technology. China's potential and progress in alternative powertrains, particularly electric batteries and fuel cells, and the global implications of China becoming a leader in these technologies would be of extreme interest for future study.

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Appendix 1: Developing Country (China) Scenario Questionnaire
Understanding the Manufacturing Cost Structure

1. Wage ranges

    - Direct Wages: ______
        - General
        - Skilled

    - Overhead Burden: ______
        - Janitorial
        - Managerial (local)
        - Ex-patriot

2. Downtime

    - Working days per year: _____
    - Working hours per day (scheduled): ______
    - Average Downtime: ______
        i. Planned worker breaks (affect operation y/n?)
        ii. Non-scheduled worker breaks (affect operation y/n?)
        iii. Planned Maintenance
        iv. Unplanned Maintenance
        v. Electricity-related non-operable time
        vi. Worker-related non-operable time

3. Yield

    - Reject Rate: _____
        i. Manual (labor) error
        ii. Mechanical (machine) error (SRIM and Assembly)
        iii. Raw material imperfections (SRIM)

iv. Component Imperfections (Assembly)

4. Scrap Rate

- ❑ Scrape Rate: ______

  Less efficient methods/equipment/labor in . . .

  - o SRIM
    - ▪ Fiber spraying
    - ▪ Resin Nozzles
    - ▪ Trimming
  - o Assembly
    - ▪ Adhesive dispenser

5. Other Financing Factors

- ❑ Capital Recovery Rate: _____%
- ❑ Capital Recovery Period: _____yrs
- ❑ Electricity Price: _____USD
- ❑ Installation Cost: _____%
- ❑ Maintenance Cost: _____%
- ❑ Price of Building Space: _____USD
- ❑ Building Recovery Life: _____yrs

6. Supply chain / Transportation Costs

Within what range can different supplies of material, component, and capital supplies be expected to change costs within each of those areas?

→ *availability, if at all, within the Chinese continent*

→ *closest (cheapest? Most feasible?) import options*

→ price *at which each product (raw material, component, or equipment) is purchased/obtained for use in US vs. China.*

→ transportation cost *to facility (both from oversea as well as then within China) of each in US vs.China. f(travel time, mode of transportation, delays, …)*

- ❑ Raw Materials
  - Glass fiber
  - Resin
  - Adhesive
- ❑ Components
  - Preformed Parts ?
  - SRIM Components
- ❑ Equipment
  - Preforming robot system
  - SRIM press
  - Adhesive system
  - Cure-fixture system
  - Supporting robots, equipment, etc.
- ❑ Tools
  - Preforming molds
  - SRIM molds
  - Fixtures ?

*** To what extent do post-production developed versus developing country transportation costs to point-of-sale affect overall costs / final sticker price?

Understanding Drivers of Technology Choice

Economic Drivers

1. Aside from wage, downtime, yield, scrap, and supply issues, can you suggest any other major developing country (China) factors causing differences in production costs?

2. What role do risk/uncertainty play in encouraging a low-investment alternative over a production system with large economies of scale?

3. What role do lower wages play in choice of manufacturing in a developing country?

   In choice of body component material?

   In choice of manufacturing methods?

4. Are there other economic (cost) factors which play a large role in choice to manufacture in and choice of material and manufacturing technologies for production within that country?

5. What percentage of automobiles being manufactured in developing countries (China) being manufactured for local demand versus for export?

   a. To what extent is this "manufacturing" assembly versus component production?

6. How does developing country (China) market demand put different requirements on vehicle bodies?

   a. Safety/crashworthiness

   b. Appearance (Class A)

   c. Form (body design)

   d. Durability

   e. Maintainability

   f. Other

Political Drivers

1. Affect of investment cap ($30M . . . to become $150M)
2. Local content requirements/incentives
3. Technology transfer requirements/incentives
4. Incentives pinpointing specific technologies
5. Investment incentives
6. Tax incentives (which, for what?)
7. Other

Technical Drivers

1. Under what conditions, if any, is the testing or production of new or early-stage technologies preferable in developing countries? Under what conditions is it important for this early-stage production not to occur in developing countries?
    a. Greenfield advantages?
    b. Forgiving safety standards?
    c. Lack of skilled labor / important R&D or other knowledge infrastructure?
    d. Loss of tacit knowledge to local regions/workers?
    e. IP problems?