Marketing Engineering Materials to the Bicycle Industry:

A Case Study for Duralcan Metal Matrix Composites

by

Jason Frederick Amaral

Submitted to the Department of Materials Science and Engineering
in Partial Fulfillment of the Requirements for the
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ABSTRACT

Duralcan metal matrix composite (DMMCs) is an advanced engineering material produced by Duralcan USA, a division of Alcan Aluminum, Inc. Because of its unique combination of cost and performance, DMMC is likely to be appropriate for applications in many manufacturing industries. Several all-terrain bicycle (ATB) applications are presently being commercialized. This thesis focuses on the policy Duralcan should follow to market DMMCs to the manufacturers of ATB applications. More specifically, the thesis identifies the combination of performance and price that Duralcan has to offer before DMMC is incorporated into designs for ATB frames, disc brake rotors, and wheel rims.

The successful marketing of an advanced material like Duralcan requires that the supplier understand the way potential customers select materials. For specific ATB applications, personal interviews were conducted using multi-attribute utility analysis (MAUA). MAUA is a preference mapping technique which was especially helpful in identifying relevant materials characteristics, in understanding decision making processes, and in evaluating alternative material choices.

Only weight and cost are traded-off for ATB frames. However, even these two objective characteristics are not sufficient to predict materials selection. It seems that while minimum property levels exist, performance is difficult to define and even harder to measure. Materials are chosen largely on the basis of subjective factors and marketing considerations; the commercial success of a new material is not easily linked to its properties. Weight, cost, and service life are traded off for ATB disc brake rotors. For the manufacturer interviewed, DMMC is preferred up to the designer's cost limit of $15 per manufactured rotor. The disc brake system offers significantly better braking performance than a traditional rim brake, but the customer must accept a higher cost and weight. Weight, cost, and service life are also traded off for ATB wheel rims. For the manufacturer interviewed, DMMC is preferred over a wide cost range up to $25 depending on the aluminum rim manufacturing cost.

Thesis Supervisor: Joel P. Clark
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1.0 Introduction

1.1 The Importance of Materials Selection to the Materials Supplier

The materials supplier's main objective is profitably satisfying its customer's demands. The traditional supplier acquires raw materials (e.g. ores, minerals, crude oil) and enhances their value through additional processing steps (e.g. crushing, smelting, refining). The materials so-processed are undifferentiated commodities which are offered in standard grades and sizes. If a need is expressed in one or more industries, the supplier may also develop higher-priced, differentiated materials. These advanced engineering materials require substantial processing, and the suppliers attempt to protect the necessary technology by proprietary knowledge and/or patents. To justify the large expense incurred in developing this second class of materials, these industries will likely be of a significant size and the intended applications will be expected to account for a large portion of eventual sales volume and revenue.

One example of a differentiated material is the family of Duralcan metal matrix composites (DMMCs - See Appendix A for all abbreviations). Metal matrix composites (MMCs) are advanced materials, conceived in the early 1950s, which are characterized by the ceramic particle, whisker, or fiber reinforcement of a metallic host. They were developed to exploit the desirable properties of ceramics (e.g. high tensile strength, elastic modulus, wear resistance) while avoiding brittle mechanical failure. DMMCs are low cost aluminum oxide (Al_2O_3) and silicon carbide (SiC) particulate reinforced aluminum matrix composites which are produced by Duralcan, a division of Alcan Aluminum Corporation (Schuster, 1993, pp. 337-348). As is commonly observed with the introduction of new materials, the envisioned large-scale customers of DMMCs have been slow material adopters and product commercialization has been encumbered.

However, as is also common, DMMCs possess properties which are attractive to other customers. For example, while the material was initially developed for military, aerospace, and automotive applications, recent emphasis has been placed on recreational and other commercial applications (Schuster, 1993, p. 341).

In order to market a new material like DMMC effectively, the supplier must understand the decision making processes of potential customers. Traditional literature on materials selection describes how an industrial designer or engineer should most effectively choose a material given a well defined product application which has a set of performance and cost requirements (e.g. Ashby, 1992; Dieter, 1983). The recommended search for the material proceeds from the general to the specific: all materials classes are initially considered and the list of options is systematically narrowed until a single material remains.

The perspective of the materials supplier is necessarily different. The supplier, having developed a material with a set of engineering and cost attributes, seeks to identify product applications by a sort of "reverse" materials selection. The reverse process requires that the supplier identify potential product applications for which its material is appropriate, determine the most promising of these applications, and then convince the product manufacturers to specify the material. This task presents formidable barriers. First, because the number of potential applications is considerable and continuously increasing, the supplier cannot hope to specify *a priori* the most promising products and manufacturers to pursue. Second, compromises between cost and performance are inherent to the selection process so it is the perceptions and preferences of the materials selector - not the materials supplier - which determine final specification. The supplier plays a passive role so it can only hope to inform and encourage customer adoption.

1.2 Statement of Thesis Purpose

To avoid a prolonged, costly, or even unsuccessful introduction, the supplier must carefully market its new material. It is proposed that the supplier identify and market to responsive customers in niche markets. By supporting "showpiece" applications for which the material offers obvious advantages, knowledge of and confidence in the material will more quickly diffuse to selectors in the intended and additional industries.

The bicycle industry appears to be responsive to new materials. This work presents a case study for the introduction of DMMCs into new and existing all-terrain bicycle (ATB) applications. The ATB, also known as the mountain bike (MTB), is a newer bicycle class that presently dominates U.S. sales. Originally intended for use on mountain trails, the ATB is presently ridden on many other uneven surfaces including forest paths, dirt roads, and city streets.

The goal of this thesis is to explore the industrial policy alternatives faced by Duralcan in marketing DMMC to the manufacturers of ATB applications. Although the bicycle industry is relatively significant, it is assumed throughout that the main intention of market development is to encourage the adoption of DMMC by large-scale customers. This work discusses the reasons a materials supplier would seek interim customers, and then presents a strategy for identifying and marketing to these customers generally and to ATB industry customers specifically. For three specific ATB applications, multi-attribute utility analysis (MAUA) was especially helpful in identifying relevant materials characteristics, in understanding decision making processes used by selectors, and in evaluating alternative material choices.

2.0 Marketing Advanced Materials in Niche Industries

2.1 Reasons for Seeking Interim Customers

It was proposed in Section 1.2 that suppliers of advanced materials should identify and market to responsive customers in existing niche markets while preparing for future large-scale customers. The traditional large-scale users in aerospace, military, transportation, and communication industries may require many years to reach full scale production especially when markets and technologies are both new. Niche customers can help materials suppliers during the transition period by generating positive cash flows, reducing costs through learning and experience, smoothly increasing production volumes to meet future demand, building and strengthening working relationships with fabricators, and developing name recognition through a history of success. These five benefits provide feedback, speed adoption, and build barriers against market entry by other suppliers once the material has been adopted.

1. Generating positive cash flows addresses the problem of "pioneer burnout." Positive cash flows may help maintain long-term management support for new products. The revenues from short-term customers, although likely to be small when compared to those possible from large-scale customers, may provide financial relief for projects unprofitable throughout their introduction phase.

2. Reducing costs through learning and experience relates to the observation that costs decrease with cumulative production experience. Thus, learning may allow the supplier to become the lowest cost producer. However, Day and Montgomery note that this is not necessarily the case (Webster, 1991, pp. 135-136). All competitors do not face

the same experience curve so later entrants may actually have the lowest cost per unit if they can avoid the original supplier's mistakes or benefit from improved technology.

3. Smoothly increasing production volumes to meet future demand helps uncover unforeseen problems which can occur during rapid production scale-ups. A gradual increase in production may increase the probability of being prepared for large-scale customers when eventual demand arises.

4. Building and strengthening working relationships with fabricators during the interim period allows the supplier to develop a competent network of fabricators. Fabricators with extensive experience working with the new material will be better able to serve large-scale users. This network also reduces the uncertainty as perceived by potential adopters.

5. Developing name recognition through a history of success addresses the problem of patent expiration - assuming that patents were useful - if market introduction is prolonged. If the supplier can prove that it is consistently able to meet demand with high quality material at stable prices, the material's trade name will be a marketable advantage.

2.2 Identification and Classification of Interim Customers

Prior to research and development, the supplier of advanced materials identifies a market need which is expressed by members of at least one large and stable industry. Research has shown that these mature industries are dominated by large firms having well defined, high volume products competing on price and dependability (Hayes and Wheelwright, 1988, p. 421). Therefore, it can be expected that a selected material provides incremental, but nevertheless valuable, benefits to the manufacturer. Since the advantage is incremental and the cost is critical, it can also be expected that the driving force for adoption is small. Certain individuals within the customer firm will be skeptical of the new material and feel that the current material works satisfactorily, is well understood, possesses reliable properties, and is readily obtainable. While the supplier must at the very least provide commercialization assistance to these customers, it should also gain their confidence by pointing to successful applications in niche industries.

Since it is impossible to pre-select all potentially successful applications, initial efforts should be concentrated on several of the most promising customers. Fast adopters could be divided into two main groups according to industry growth. The first are in industries experiencing rapid short term growth. Table 2-1 lists the U.S. Department of Commerce predictions of the ten fastest-growing manufacturing industries for 1994 (Menes, 1994, pp. 18, 22-23). Since varied product designs could be expected to accompany rapid growth, there will likely be products for which development is limited by current materials. If the supplier can offer a material with the required combination of properties, firms in this first group are potential fast adopters. Hayes and Wheelwright note that intra-industry competition will be based on product characteristics (Hayes and Wheelwright, 1988, p. 422). Because these firms are receptive to any material which solves their problems, they are likely be less price sensitive and thus a good source of revenue.

Table 2-1: The Ten Fastest-Growing U.S. Manufacturing Industries in 1994.

SIC	Industry	Value of Industry Shipments 1994	Growth Rate 1993-94 (percent)	Compound Annual Growth 1987-94 (percent)
3541	Machine tools, metal cutting types	3.636	12.8	1.9
367	Electronic components and accessories	93.767	11.1	9.3
3842	Surgical appliances	14.488	10.0	7.9
2451	Mobile homes	5.765	9.4	5.0
371A	Automotive parts and accessories	107.158	7.7	2.1
3841	Surgical and medical instruments	11.769	7.0	6.1
364A	Lighting fixtures	6.425	6.6	0.5
2515	Mattresses and bedsprings	3.030	6.4	3.3
3111	Leather tanning and finishing	2.202	6.0	-0.1
3826	Analytical instruments	5.210	6.0	6.0

Notes: Value of shipments is in billions of 1987 dollars. Percent change is based on 1987 dollar shipments. *Source: U.S. Department of Commerce.*

The second group is in industries experiencing solid growth over a period of years. Table 2-2 lists U.S. Department of Commerce predictions of the ten fastest-growing manufacturing industries for 1987-1994 (Menes, 1994, pp. 21-23). This type of growth is consistent with increasing standardization and product competition based on quality and availability (Hayes and Wheelwright, 1988, p. 422). The second group of applications are likely to be superior products which are delivered at a reasonable cost. Firms in this group which commercialize the advanced material help to encourage the adoption by large scale users.

Table 2-2: The Ten Fastest-Growing U.S. Manufacturing Industries, 1987-1994.

SIC	Industry	Value of Industry Shipments 1994	Compound Annual Growth 1987-94 (percent)	Growth Rate 1993-94 (percent)
3824	Fluid meters and counting devices	1.996	11.4	1.0
3844	X-ray apparatus and tubes	3.279	11.3	5.0
2835	Diagnostic substances	4.542	10.9	2.0
367	Electronic components and accessories	93.767	9.3	11.1
3751	Motorcycles, bicycles, and parts	1.906	8.7	2.6
3842	Surgical appliances and supplies	14.488	7.9	10.0
3769	Space vehicle equipment, nec	1.980	7.6	-3.9
3088	Plastic plumbing features	1.161	7.3	4.0
3845	Electromedical equipment	5.799	7.1	0.2
2833	Medicinals and botanicals	5.429	7.1	1.9

Notes: Value of shipments is in billions of 1987 dollars. Percent change is based on 1987 dollar shipments. The abbreviation "nec" represents "not elsewhere classified." *Source: U.S. Department of Commerce.*

After identifying several industries, the supplier should narrow its search to specific companies. Formal industry information sources (e.g. directories, publications, associations, trade shows) will facilitate this process, as will informal information sources (e.g. contacts developed through daily business communication). To learn about the industry generally, a directories can be used to contact firms, trade associations, and consultants, and to obtain publications. Leads can be pursued to identify the most promising product applications and the more innovative firms. At this stage, the supplier should concentrate on identifying the most obvious applications and firms, and not on selling material.

The person or persons responsible for materials selection at promising manufacturers should be contacted. The supplier should determine whether the products identified are good applications of the material or whether other applications would be better suited to the material's properties. These designers will know what is required and what types of properties are desired. Those applications for which the new product appears to offer significant advantages should be considered for further marketing.

Complementing the search for potential products described above, the supplier should work with its actual customers - the fabricators. This more traditional route should also be followed because a strong fabricator network is required for successful commercialization. The fabricators are closer to the end user and have a different perspective so they may be able to suggest additional potential applications.

So that the proper firms are chosen for support, the final part of the strategy for identifying fast adopters involves understanding the situations of the fabricators and end-product manufacturers. According to Corey, the willingness of a fabricator (and probably also of a manufacturer) to make and sell new products depends on several factors (Corey, 1956, pp. 15-16). The first factor is whether significant organization and/or production changes are needed and, if so, the time and monetary costs which are incurred. The second factor is whether new product sales will come at the expense of existing product sales, or if the new products will serve different market segments. The third factor is whether the new product will give the firm a competitive advantage over other firms in the current or new markets. The potential customers that are identified as fast adopters of new materials should be seriously considered for market preparation.

The main goals of marketing to interim customers is to encourage more rapid adoption of large scale customers and to strengthen the supplier's ability to provide the new material. The selected product applications should thus have distinguishing advantages which are readily associated with the special properties of the new material. This will enable product successes to be strongly linked with the new materials in the minds of large-scale users. Especially at this stage, the supplier should be cautious that the material is not used for inappropriate applications and that it is not used improperly for appropriate applications (Corey, 1956, p. 244). Certain fabrication skills will be required for the large-scale users, so favored interim applications should help strengthen the required skills.

The supplier will not be able to identify all the appropriate applications for the new material, but initial marketing successes may encourage other potential users to come forward. The supplier may be able to stimulate and sustain interest by advertising successful applications in the appropriate trade journals and inviting inquiries concerning additional applications.

2.3 Adoption of Advanced Materials by Interim Customers

In developing a market for new materials, the supplier must build a strong network of fabricators which can offer semi-finished products (Corey, 1956, pp. 15-56), and stimulate demand for the new material among manufacturers of end-products (Corey, 1956, pp. 59-131). This dual role may be problematic if fabricators perceive it to be competition for manufacturer loyalty (Corey, 1956, p. 232). Also, if the supplier initially concentrates all its efforts on solving technical problems and only addresses the needs of manufacturers and end-users when the market fails to develop as quickly as anticipated, the supplier may be perceived as critical of its fabricator-customers' abilities (Corey, 1956, p. 234). Both situations can be avoided if the supplier and fabricator develop a clear, up-front understanding of how they will share risks and rewards (Webster, 1991, pp. 181-182).

When selecting the focus of the marketing drive, the supplier must carefully consider who has the greatest incentives to see the material adopted, who can most significantly facilitate adoption, and who may most strongly resist adoption (Corey, 1956, pp. 97-98). Throughout market preparation, it must be remembered that this interim development should build and strengthen ties with fabricators, so the concerns of these fabricators should be addressed. The supplier must decide whether to market at the fabricator level, at the manufacturer level, or at both levels.

Even within a customer group, the fabricators or manufacturers which should be most actively pursued are not obvious. Corey notes that the market leaders may not perceive the greatest opportunities for gain (Corey, 1956, p. 34). First, the products made of the new material may compete with existing, successful products, and second a product failure with the new material could damage the leader's reputation. Aggressive smaller fabricators and manufacturers could perceive an opportunity to gain a significantly strengthened market position. If so, the success of smaller fabricators and manufacturers, although possibly requiring technical or financial assistance from the supplier, may encourage the leaders to adopt to remain competitive.

Research into the diffusion of innovations provides some insight into the likelihood of a potential customer to adopt the new material. Several generalizations about earlier adopters as compared with later adopters of innovations are listed below (Rogers, 1983, p. 260-261).

1. Socioeconomic Characteristics

Earlier adopters

- Have more years of education
- Have a higher social status
- Work in larger sized companies
- Have more specialized operations

2. Personality Variables

Earlier adopters

- Have greater ability to project themselves into the roles of others
- Have a greater ability to deal with abstractions
- Have greater rationality
- Have greater intelligence
- Have a more favorable attitude toward change
- Are more able to cope with uncertainty and risk
- Have a more favorable attitude toward science
- Believe that they are in control of their futures
- Have higher levels of achievement motivation
- Have higher aspirations

3. Communication Behavior

Earlier adopters

- Have more social participation
- Are more highly interconnected in the social system
- Are more likely to be involved in matters outside their local system
- Have greater exposure to mass media communications
- Have greater exposure to interpersonal communications
- Actively seek information about innovations
- Have greater knowledge of innovations

It is most important at this stage for the supplier to assess the environment. To identify a customer for market development, the supplier should keep the general characteristics of faster adopters in mind.

Diffusion research also provides guidance for methods of encouraging the adoption process. It is generally accepted that adoption is not an instantaneous action, but that it is a progression through several stages. Rogers identifies five stages of the "innovation-decision process," although he admits that there is little agreement on the number or names of stages (Rogers, 1983, pp. 163-164).

1. Knowledge: The individual is exposed to the existence of the innovation and gains some understanding of its functions.

2. Persuasion: The individual forms a favorable or unfavorable attitude toward the innovation.

3. Decision: The individual engages in activities which lead to either the adoption or rejection of the innovation.

4. Implementation: The individual uses the innovation.

5. Confirmation: The individual seeks reinforcement of the decision's appropriateness, but may reverse the previous decision if conflicting messages are received.

Rogers and Shoemaker note that the attributes of the innovation can affect the rate of adoption so the supplier should "package" the innovation according to the needs of the individual (Rogers and Shoemaker, 1971, p. 135). In other words, the supplier should emphasize the material's properties that make it most suitable for a given application.

As expected, information about the innovation is required throughout the process and Webster identifies several sources of information which include sales representatives, employees of other companies, and technical journals (Webster, 1991, p. 162). Webster further notes research that shows sales representatives to be the most important source of information at each stage except at the awareness stage where trade journals are slightly more important (Webster, 1991, p. 163). Rogers and Shoemaker note that rejection could occur at any point in the decision process (Rogers and Shoemaker, 1971, p. 113). For instance, individuals can forget about the innovation after they are aware or discontinue use after they have adopted. Rogers and Shoemaker also emphasize that certain attributes should be emphasized at various stages in the process so a marketing strategy should be dynamic (Rogers and Shoemaker, 1971, pp. 159-160).

The above observations about innovation diffusion are relevant to the diffusion of advanced materials. When the individual is first exposed to the new material at the awareness stage, the supplier should highlight the material's compatibility with existing needs through trade journal articles and sales representatives. When the individual is forming an opinion at the persuasion stage, the relative advantage of the innovation in terms of increases in profitability, reductions in perceived risk, and immediacy of return should be accented. Additionally and if applicable, the supplier should emphasize the degree to which the innovation has been adopted by others. These persuasion stage tasks should be accomplished through sales representatives, trade journal articles, and trade show attendance. At the decision stage, the sales representatives should provide the individual with detailed property specifications as well as samples for prototyping. The supplier should also put the individual in contact with engineers and designers at other companies who have already adopted the material.

3.0 Market Analysis of the All-Terrain Bicycle Industry

3.1 Bicycle Industry Statistics

As was shown in Table 2-2, the industry for motorcycles, bicycles and parts is forecast to be the fifth fastest growing manufacturing industry from 1987 to 1994 (Menes, 1994, pp. 21-23). Furthermore, of the $1.9 billion in forecast 1994 product shipments, $1.1 million is accounted for by bicycles and parts (Vanderwolf, 1994, pp. 37—6, 9). Figure 3-1 shows the growth of the U.S. market for bicycles and parts, after accounting for exports, from 1988 to 1993 (Vanderwolf, 1994, p. 37—6). The domestic market was valued at $1.8 billion in 1993 (Vanderwolf, 1994, p. 37—6). According to other sources, the approximate retail value of the market is between $3.5 and $4.5 billion, including the value of the bicycles, related parts, and accessories sold through all distribution channels (*Interbike Directory*, 1994, p. 218; National Bicycle Dealers Association, 1994, p. 1).

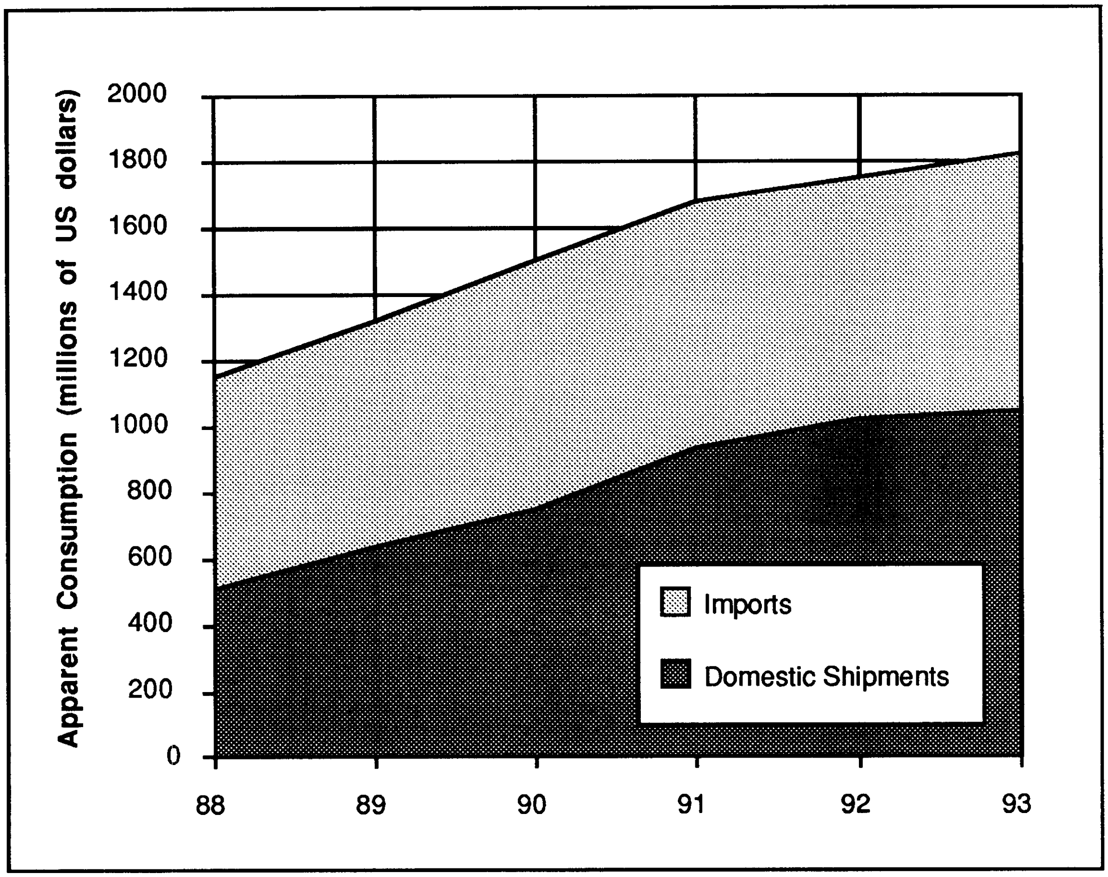


Figure 3-1: U.S. Market Value by Origin for Bicycles and Parts, 1988-1993. (Domestic Shipments = Product Shipments - Exports; Apparent Consumption = Domestic Shipments + Imports). *Source: U.S. Department of Commerce (Vanderwolf, 1994, p. 37—6).*

The annual bicycle production in 1991 was reported at more than 100 million units worldwide and approximately 7.6 million units in the United States (*Interbike Directory*, 1993, p. 219). Figure 3-2 shows the U.S. sales by bicycle origin (Bicycle Institute of America, 1993, p. 7). The 1993 U.S. bicycle market was estimated at 11.6 million (Bicycle Institute of America, 1993, p. 7). The record high sales year for bicycles was 1973 when 15.2 million bicycles were sold (National Bicycle Dealers Association, 1994, p. 1).

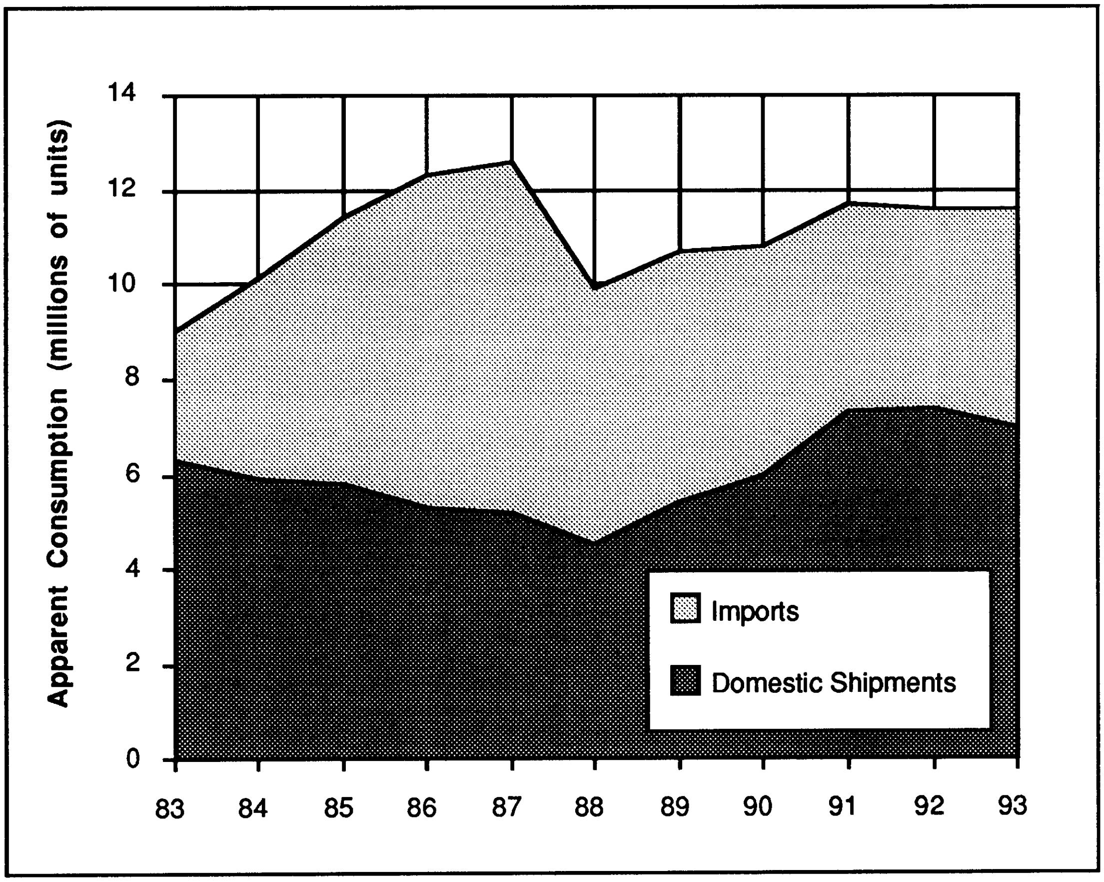


Figure 3-2: U.S. Market Size by Origin for Bicycles, 1983-1993. (Domestic Shipments = Product Shipments - Exports; Apparent Consumption = Domestic Shipments + Imports). *Source: Bicycling Manufacturers Association of America (Bicycle Institute of America, 1993, p. 7).*

In 1991, 72% of all units were sold by mass merchants (e.g. K-Mart, Sears, Toys-R-Us, WalMart), 24% were sold by traditional bike shops (i.e. independent bicycle dealers or IBDs), and 4% were sold by other retailers (e.g. outdoor shops, sporting goods stores, mail order outfits) (National Bicycle Dealers Association, 1994, p. 2). However, because of their heavy emphasis on inexpensive, general purpose bicycles, only 52% of bicycle sales in 1989/90 went to mass merchants, with 41% to IBDs, and 7% to other retailers (National Bicycle Dealers Association, 1994, p. 2). Figure 3-3 shows the U.S. market share in 1993 according to price range for bicycles sold by IBDs (*Interbike Directory*, 1994, p. 218). IBDs dominate the sales for parts and accessories at 66% of sales, with 12% to other retailers and 22% to mass merchants (*Interbike Directory*, 1993, p. 222).

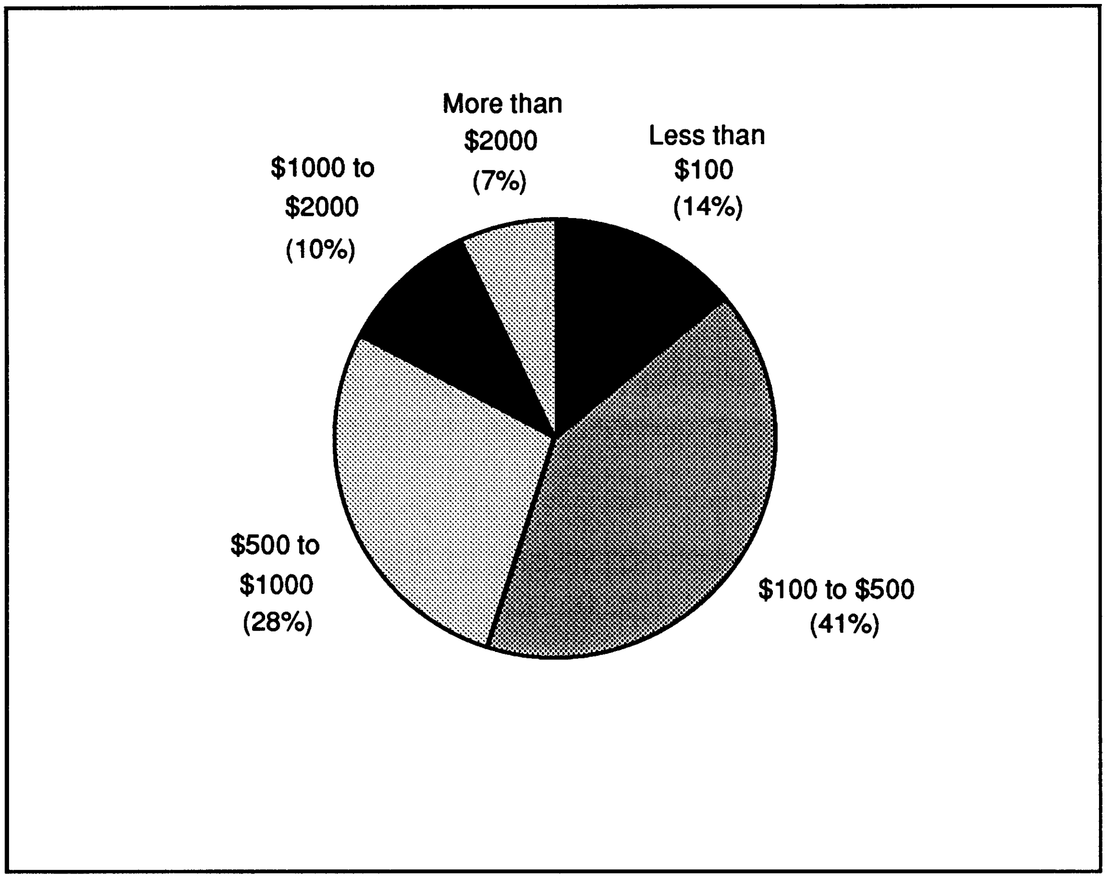


Figure 3-3: U.S. Market Share by Price Range for Bicycles Sold by Independent Bicycle Dealers, 1993. *Source: Bicycle Retailer & Industry News (Interbike Directory, 1994, p. 218).*

Although the sales growth of bicycles has generally been positive, the market shares by bicycle type is changing. Figure 3-4 shows U.S. sales by bicycle type from 1983 to 1992 (Bicycle Institute of America, 1993, p. 7). Overall, traditional road bikes have lost share to ATBs.

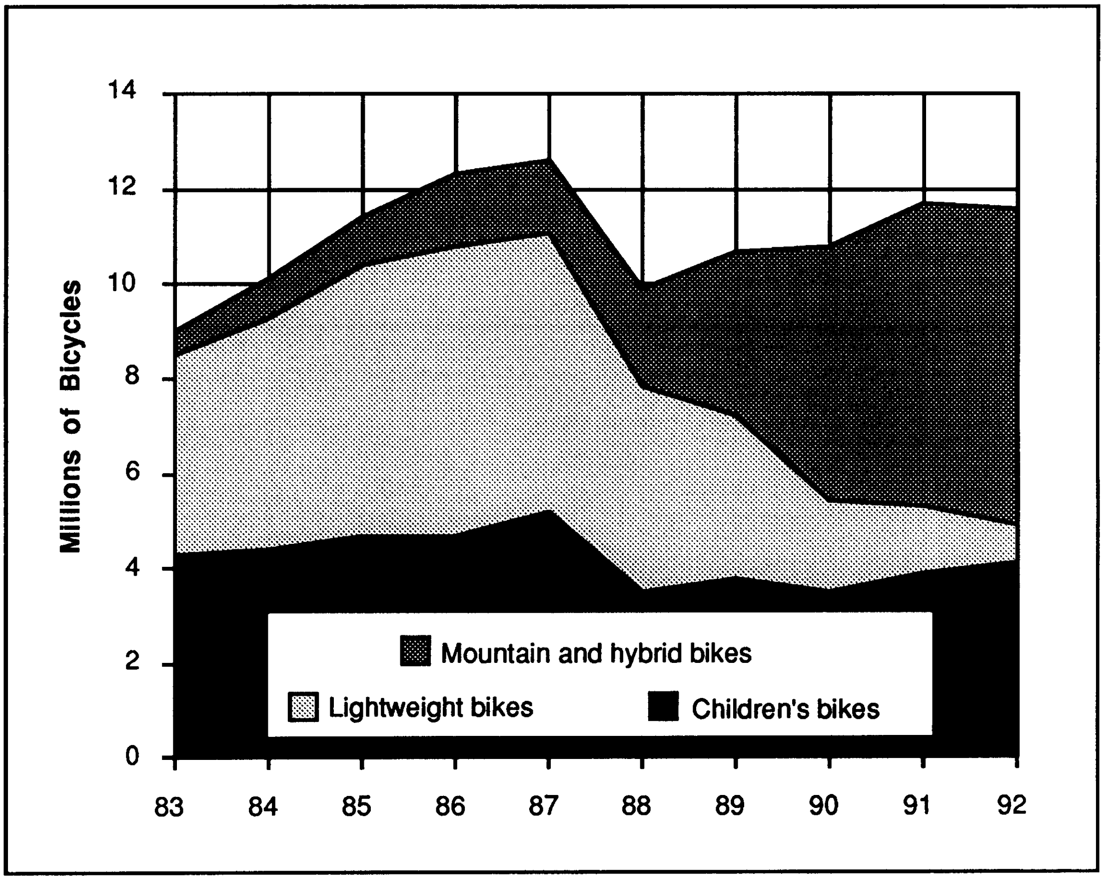


Figure 3-4: U.S. Market Size by Type for Bicycles, 1983-1992. *Source: Bicycling Manufacturers Association of America (Bicycle Institute of America, 1993, p. 7).*

The declining market share of lightweight bikes is especially evident for sales through the higher end IBD channel. Figure 3-5 shows U.S. sales by type for bicycles sold by IBDs from 1988 to 1993 (Bicycle Wholesale Distributors Association, 1994, p. 4). In 1993, less than 1% of all bikes were lightweights and 80% were either MTBs or hybrid bikes.

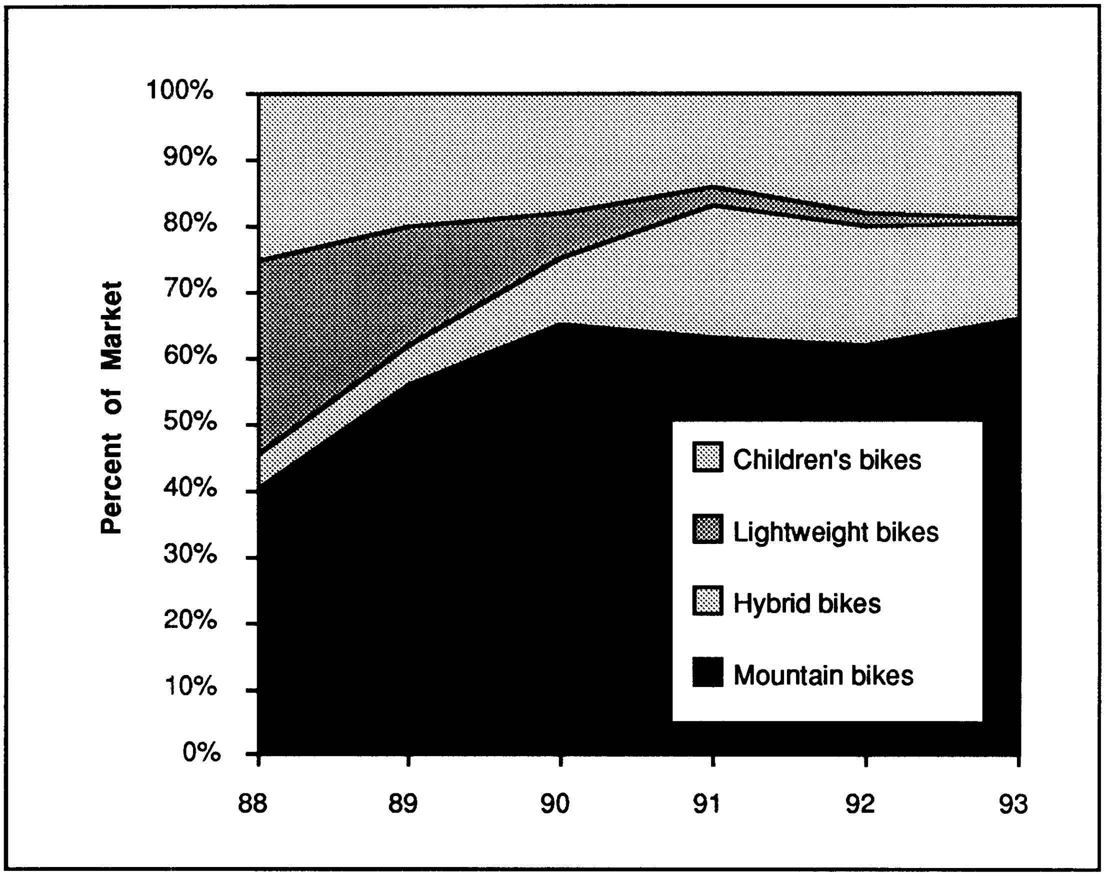


Figure 3-5: U.S. Market Share by Type for Bicycles Sold by Independent Bicycle Dealers, 1988-1993. *Source: Bicycle Wholesale Distributors Association (Bicycle Wholesale Distributors Association, 1994, p. 4).*

With the number of frequent participants increasing 170% between 1988 and 1991, mountain bikes rate as the second highest sports growth area after stair-climbing machines (*Interbike Directory*, 1993, p. 222). Figure 3-6 shows the U.S. MTB usage from 1983 to 1992 (Bicycle Institute of America, 1993, p. 6). There were 25 million mountain bikers as of 1992 and an estimated 30 million in 1993 (Bicycle Institute of America, 1993, p. 6).

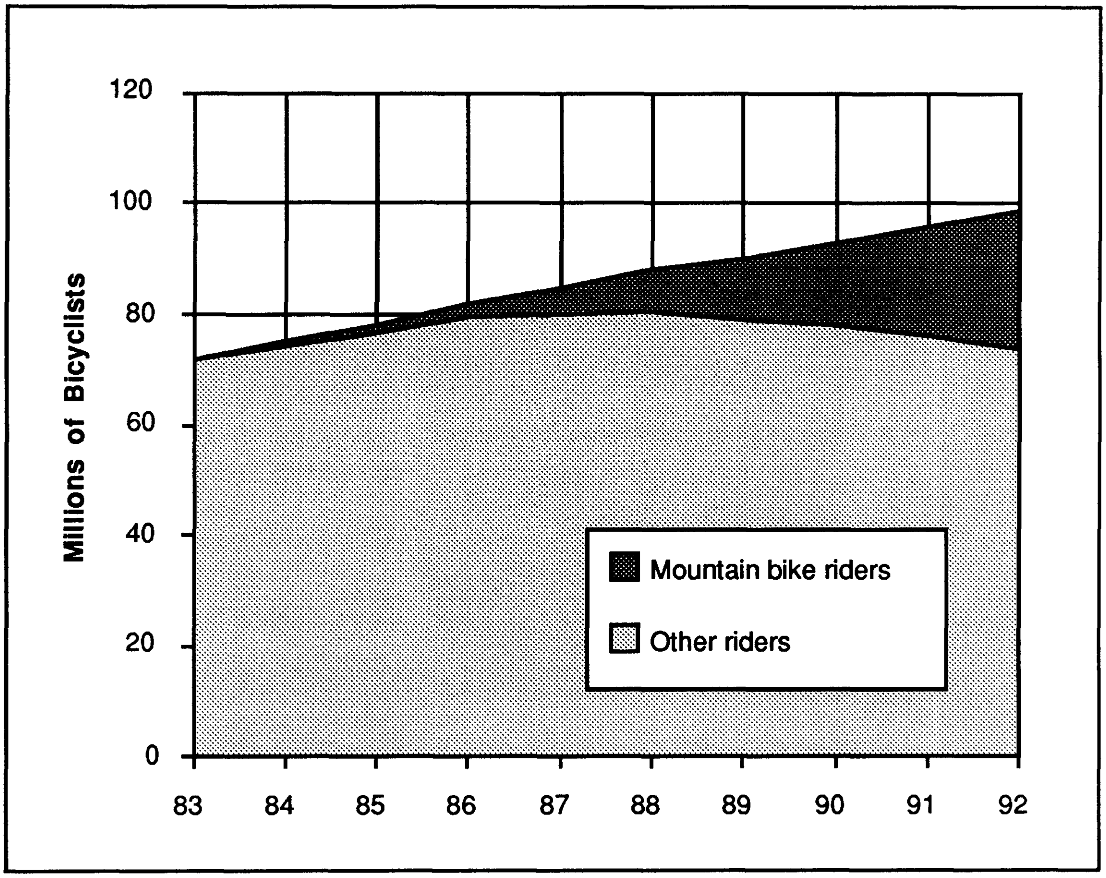


Figure 3-6: U.S. Mountain Bike Usage, 1983-1992. *Source: Bicycling Manufacturers Association of America (Bicycle Institute of America, 1993, p. 6).*

3.2 A Brief History of the Bicycle Industry

The first true bicycle was designed in 1839 by a Scottish blacksmith named Kirkpatrick Macmillan and substantial developments in tires, frame geometry, and gearing took place in Europe and America until the early twentieth century (Whitt and Wilson, 1982, pp. 3-28). Although design refinements were made over the next fifty years, the industry gradually became less innovative as racing rules forbade unconventional human powered vehicles. Classic attitudes changed during the 1970s and 80s and alternative bicycle classes such as the recumbent, the triathlon bicycle, and the ATB became more widely accepted. For example, because ATB participants were not bound by design tradition or racing rules and because they rode under extreme conditions, ATB builders sought to improve durability, stability, traction, comfort, and weight by incorporating non-traditional materials and technologies (Sloane, 1985, p. 9).

3.3 Customer Groups of Advanced Materials in the All-Terrain Bicycle Industry

New materials appear to get adopted into the ATB market by one of four ways. The first way is by well respected individuals who have been riding on mountain trails since the beginning of the ATB industry. These "industry gurus" manufacture products involving unique designs and non-traditional materials. The products are normally produced at low volumes and sold in the after-market to enthusiasts. If these products are successful in the after-market, they are frequently adopted by original equipment manufacturers (OEMs). The gurus may not fully understand the interactions between shape, material, and processing; they evaluate design performance instead by intuition and experience. A frequently heard story features the guru who makes a frame or component out of an "aerospace" material being offered commercially for the first time.

The design, usually adapted from existing bicycle or motorcycle products, is refined until the desired performance is achieved.

The second way new materials are adopted is by "technical leaders" who have well established, high quality designs and clear product requirements. This group is characterized by larger, up-scale firms with a high level of engineering and manufacturing ability. Using their understanding of materials attributes and design implications, these firms perform two roles. First, they redesign and commercialize successful and unsuccessful after-market products as original equipment. Second, they introduce original designs which were either developed in-house or adapted from products outside the cycle industries.

The third way new materials are adopted is by "garage shops" who capitalize on a new materials growing reputation by copying old designs without offering substantial advantages over the original. To these builders, the allure surrounding a material is much more important than the material's properties.

The fourth way new materials are adopted is by "copy-cat" firms. These firms are traditionally based off-shore and simply mass-manufacture successful designs. They are able to offer their products at discounted prices because of lower manufacturing costs and negligible development costs.

It is important that the materials supplier understand to which idealized group a potential niche customer belongs. The lack of design sophistication is a risk with a guru group, because a product failure due to incorrect shape or processing could mar the material's reputation. Materials suppliers should not support the garage shop group because inappropriate applications can blur the perceived advantages of the material while over-marketing can cheapen its reputation. The supplier should not initially concern itself with members of the copy-cat group, because these firms are unlikely to be the first adopters of any new material. Over time they can become important by using large quantities of materials manufacturing lower end ATB frames and components. Therefore, the supplier should first concentrate on the industry leaders. The engineering competence and experience of these firms makes sound applications of the material likely.

4.0 Materials Performance Requirements for All-Terrain Bicycle Applications

4.1 Introduction

The ATB is comprised of a frame, a front fork, and associated components. The frame supports structural loads and is the element where materials choice is most obvious. However, less than 20% of a typical 20 to 30 pound ATB is due to the weight of the frame. The weight of the complete bike is greatly affected by component choice. For instance, the rider can save about a pound by switching from regular-issue tires to after-market tires ("How to Save Weight," 1993, pp. 164-165).

The frame, the disc brake rotor, and the wheel rim were the ATB applications chosen for in-depth study. Each of these applications has received considerable attention as candidates for DMMC. To gain insight into the materials selection process used by manufacturers, information was gathered from published sources and through telephone and personal interviews.

4.2 Frames

Successful ATB frames have been made from steel (chrome-molybdenum or "chromoly," manganese, medium carbon, and high carbon), aluminum (6XXX and 7XXX series alloys), aluminum metal matrix composites (DMMC from Duralcan with Al_2O_3 particulate, and Boralyn from Alyn Corporation with boron carbide, B_4C, particulate), titanium (3%Al/2.5%V, 6%Al/4%V, and commercially pure) and carbon fiber/epoxy (Kukoda, 1993; "Steel Alternatives," 1993). While each material has its ardent supporters, none stands out as the dominant choice and many observers suggest that the best frames will incorporate several different materials (Bontrager, 1993, pp. 166, 168, 171; "Is Aluminum Doomed?," 1993, pp. 163-164; Kukoda, 1992, pp. 98-102, 106; "Specialized Stumpjumper," 1991, pp. 32-36, 102-103; "Unveiling the Secrets," 1993, pp. 172-174). The DMMC frame is manufactured by Specialized Bicycle Components, Inc. Specialized refers to the material as the M2 and the ATB is called the Stumpjumper M2 MTB (Specialized Bicycle Components, Inc., 1993, p. 5). The Boralyn MMC frame is manufactured by Univega and the ATB is called the Boralyn S8.9 MTB (Lawee, 1993).

The use of other materials has met with less success. A $26,000 beryllium frame manufactured by American Bicycle Manufacturing with material supplied by Brush Wellman, Inc. was far too expensive for most consumers (Kukoda, 1993, p. 92). Aluminum-beryllium alloy frames could be more affordable ("Is Aluminum Doomed?," 1993, p. 164; McConnell, 1994, p. 21). For several years Kirk Precision, Ltd., owned by Hydro Magnesium, die cast one-piece magnesium frames. Although processing problems were being addressed, the firm was forced to close because demand did not support profitable production volumes ("Building a Better Bicycle Frame," 1988, p. 37; "Hotline," 1993, p. 12; "Steel Alternatives," 1993, p. 7).

A traditional diamond-shaped tubular construction frame is shown in Figure 4-1. With the growing popularity of "suspension" ATBs and the increasing interest in finite element analysis and computer aided design, frame shapes are likely to change (Hull and Bolourchi, 1987, pp. 61-72; Kubomura, et. al., 1990, pp. 2216-2223; Michaeli, et. al., 1991, pp. 46-48; Okubo and Ishida, 1991, pp. 860-865). Figure 4-2 shows three examples of non-traditional frames. ATBs are currently classified as either rigid (frames without suspension), front suspended (frames with a front suspension fork), or fully suspended (frames with rear suspension and a front suspension fork, also called dual suspension). Additionally, Allsop, Inc. offers a suspension system which incorporates a flexible seat strut to cushion the rider (McConnell, 1994, p. 20). Unless otherwise specified, "frame" hereafter refers to a rigid frame such as the one shown in Figure 4-1.

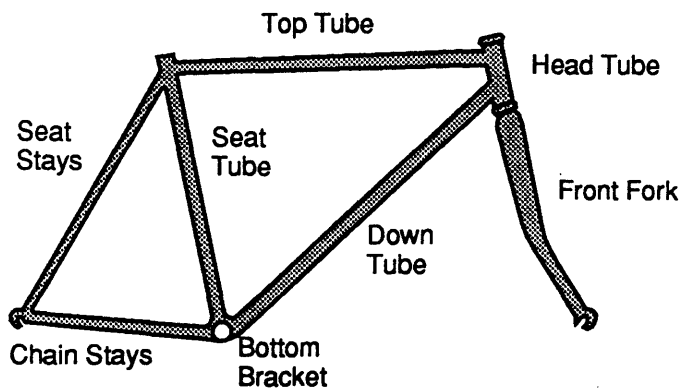


Figure 4-1: Schematic of a Traditional Bicycle Frame.

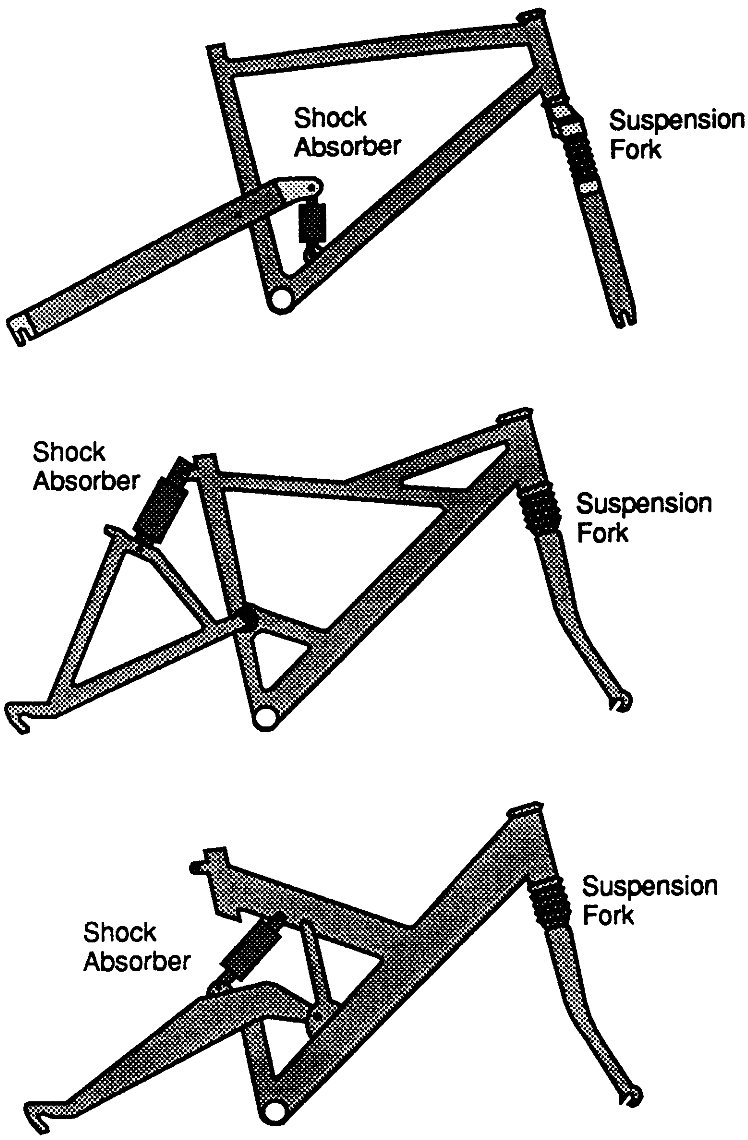


Figure 4-2: Schematics of Modern All-Terrain Bicycle Frames. Top design is similar to a frame by Trek Bicycle Corporation. Bottom two designs are similar to frames by Cannondale Corporation.

Metallic frame tubes are normally seamless drawn and may be thin in the middle to save weight and thick at the ends to handle applied loads and bending moments. This variable thickness tubing is referred to as being "butted," and tubes having two or three different wall thicknesses are "double butted" or "triple butted" respectively. Desired frame performance may be obtained by adjusting tube size and cross section as well as frame geometry. These tubes can be joined using brass brazing with lugs, brass brazing without lugs (i.e. fillet brazing), tungsten inert gas (TIG) welding, metal inert gas (MIG) welding, or adhesive boding with lugs ("Guide to Bicycle Frames," 1992, pp. 136-140; Sloane, 1985, pp. 47-50; Whitt and Wilson, 1982, pp. 239, 251-252).

In lug brazing, brass is melted and is allowed to flow via capillary action between the tube and a pre-heated socket called a lug. In fillet brazing, a brass joint called a fillet is built up gradually and filed to a smooth radius. TIG welding is done in an inert gas environment (usually argon or helium) and uses a tungsten electrode to form a high intensity electric arc. The welded joint contains a small quantity of material either from a separate weld-metal rod or from the parent metal. In MIG welding, a consumable electrode is used. The electrode material, which is fed directly through the center of a torch, fills the weld joint. In bonding, tubes are joined using close fitting lugs and thermosetting adhesives. A more complete description of these processes may be found in most manufacturing texts (e.g. Kalpakjian, 1992).

Carbon fiber/epoxy frames are manufactured from weaved and layered carbon fibers which are embedded in an epoxy matrix ("Guide to Bicycle Frames," 1992, pp. 144, 147; Kim, 1990, pp. 53-55). The composite may be either wrapped to form tubes which are later adhesively bonded with lugs, or else laid into a large mold to form a one-piece "monocoque" frame. The monocoque frame is said to be stronger than the tube frame but is also more expensive because a unique mold is required for each frame size produced (Kim, 1990, p. 55).

Frame manufacturers are most interested in performance characteristics which contribute to cost, weight, and service life. Service life is an encompassing measure which is a function of properties such as fatigue-limit strength, ultimate tensile strength, toughness, wear resistance, resistance to environmental degradation (e.g. corrosion), and impact strength. High material stiffness (elastic modulus) was generally found to be important only to the extent that it allowed a lighter frame of equivalent stiffness to be designed. At least one published source, however, reports high frame stiffness may be desirable as full-suspension bikes (Figure 4-2) increase in popularity ("Guide to Bicycle Frames," 1992, p. 142). Power transfer with rigid frames would be more efficient and suspension components would ensure a comfortable ride. The low density and high modulus of DMMC would be attractive to fully suspension rame manufacturers.

4.3 Disc Brake Rotors

ATBs presently use rim brakes and disc brakes. The rim brake is most popular type of brake and utilizes two pads, usually of a rubber composition, which are forced against the side surfaces of the wheel rims. A center-pull cantilever rim brake schematic is shown in Figure 4-3.

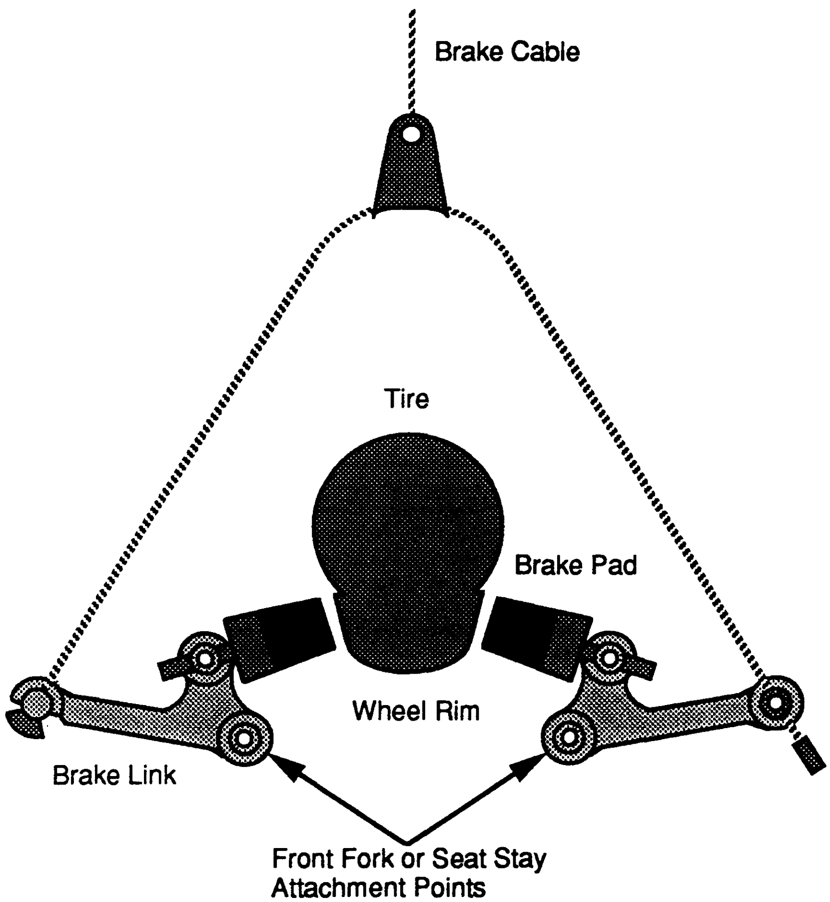


Figure 4-3: Schematic of a Cantilever Rim Brake.

Disc brakes have gear or hydraulically operated pads which press against both sides of a rotor. The rotor normally has holes in it to reduce component weight and to allow for better air cooling. A schematic of a hydraulically operated disc brake is shown in Figure 4-4. Disc brakes rotors have been manufactured out of stainless steel and hard anodized aluminum.

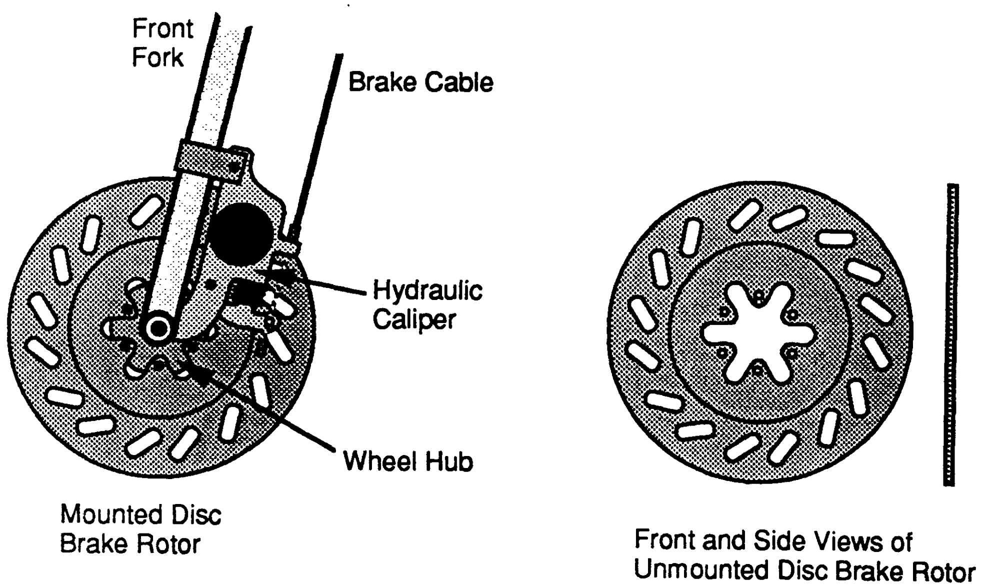


Figure 4-4: Schematic of a Hydraulically Actuated Disc Brake. Design is similar to a brake by Dia-Compe USA. The wheel spokes are not shown but connect to the wheel hub behind the disc brake rotor.

The braking force for rim brakes is applied at a large radius and almost directly to the rotating mass, so these brakes are the lightest of the two types. Rim brakes, however, have several drawbacks. Their braking power falls-off considerably when the rims are wet and consistent wet/dry braking is virtually impossible. According to Whitt and Wilson, wet coefficient of friction was reported at less than a tenth of the dry value for standard black rubber on nickel-chromium plated steel (Whitt and Wilson, 1982, pp. 191, 203). Aluminum rims, today's virtual standard, give more consistent braking because they have both a lower dry coefficient of friction and a higher wet coefficient of friction than steel (Whitt and Wilson, 1982, pp. 206-207). Break pads are also sensitive to wear by the rim and require adjustment and replacement. In addition, under the dirty braking conditions most ATBs face, the wear is mutual as the rim metal can be gouged by trapped grit. In the case of the now standard aluminum rims, metal slivers can also become embedded in the brake pads and oxidize to form abrasive aluminum oxide (Whitt and Wilson, 1982, p. 207). These brakes also perform badly on rims which are out of true (Union Fröndenberg USA Co., 1993).

Disc brakes have an effective braking diameter which is much less than the wheel diameter and a braking torque which must be transmitted through the hub and spokes, so these brakes require a high braking force and therefore a very wear resistant rotor with a high coefficient of friction (Whitt and Wilson, 1982, pp. 191, 206). The high braking force and disc positioning away from wheel spray and mud result in a much more uniform wet/dry/dirty braking response (Whitt and Wilson, 1982, pp. 191, 206). Disc brakes are able to withstand severe braking conditions because tire inner-tube puncture from rim overheating is not at issue (Union Fröndenberg USA Co., 1993). Additionally, the mounting of rim brakes on non-traditionally shaped frames is often more difficult than the mounting of disc brakes (Union Fröndenberg USA Co., 1993).

A persistent problem with disc brakes is the higher cost and added weight. However, since rims must no longer withstand wear or dissipate friction heat, lighter rim designs could partially offset the latter disadvantage. Several rim designers cautioned that rim spoke holes must remain durable and rims must still withstand severe impacts. Also, stronger (and heavier) spokes may be required to withstand larger braking torques.

DMMC shows excellent promise for disc brake rotors because of the material's light-weight and high wear resistance.

4.4 Wheel Rims

Most wheel rims for ATBs are made of aluminum, although steel rims can be found on low end mass merchant bicycles and polymer composite spoke wheels can be found on high end racing ATBs. Figure 4-5 shows schematics of a wheel rim and wheel rim cross-sections. Rim wear and a consistent wet/dry/dirty braking response are important factors when considering rim materials. To combat these problems, rim walls have been plasma and flame spray coated with oxides, but these coatings are cracked by trail-side shocks. Rim weight savings are especially significant because wheels must be given the translational kinetic energy of the bicycle as well as their own rotational kinetic energy. A kilogram in the rim thus requires more power to accelerate than a kilogram in the frame (Whitt and Wilson, 1982, pp. 127-128). DMMC, because of its light-weight and high wear resistance, has gained the serious attention of rim manufacturers.

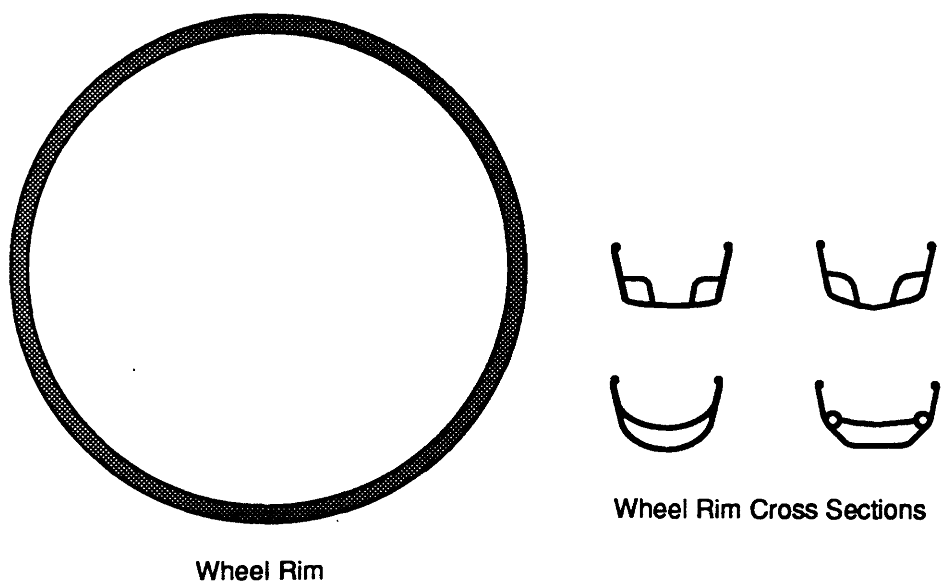


Figure 4-5: Schematics of a Wheel Rim and of Wheel Rim Cross Sections.

5.0 Multi-Attribute Utility Analysis for All-Terrain Bicycle Applications

5.1 Introduction

For suppliers to market an advanced material like DMMC successfully, they must understand the way potential customers select materials. The selection process is complicated since optimizing a design normally requires that the engineer consider multiple objectives. For example, designers attempt to balance the often conflicting objectives of maximizing performance and minimizing cost.

Most systematic techniques rely on either screening or weighting (de Neufville, 1990, pp. 173-193; Field and de Neufville, 1988, pp. 378-382). When using screening techniques, the selector sets ever-tighter performance requirements and progressively eliminates options from further consideration. The greatest disadvantage with this technique is that it favors compromise choices (average cost and average performance) over extremes (high cost and high performance, or low cost and low performance), although the latter materials may be appropriate. When using weighting techniques, the selector first applies arbitrary normalization or weighting factors to each important performance characteristic. Materials are then ranked according to a summation of the various normalized characteristics. The greatest disadvantage with this technique is that trade-offs between the characteristics are set arbitrarily, and are kept constant over the range of interest. Additionally, material ranking can be affected by the choice of normalizing constants.

An alternative method is called multi-attribute utility analysis (MAUA). This technique considers the utility or "value" of each alternative. It measures the relative, non-linear weighting of multiple performance characteristics and explicitly ranks materials according to the multi-attribute utility (MAU) provided; the materials decision-maker can determine whether a particular combination of materials performance characteristics is preferred to another. For many engineering products (e.g. automotive parts and electronic circuit boards), research has shown that MAUA allows materials selection to be based on objective performance criteria (Field, 1988; Mangin, 1993; Ng, 1990; Thurston, 1987). MAUA helps designers effectively select from an ever-growing list of available materials by allowing the direct comparison of performance trade-offs. More importantly for the materials supplier, MAUA helps predict the combination of materials attributes which best satisfy their customers' demands as well as identify competitive threats to or opportunities for their specific material.

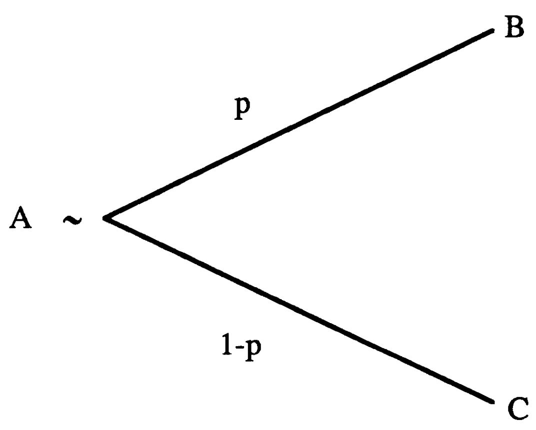
MAUA can be divided into four stages: performance evaluation, utility estimation, data reduction, and utility analysis (Ng, 1990. pp. 74-82).

1. Performance Evaluation: The specific application is analyzed and the performance characteristics relevant to the materials selection problem are defined. Of these characteristics, several are removed from further consideration because they are not traded-off. Binary characteristics are first removed. These characteristics are those for which a minimum level of performance is required, but for which additional improvements in performance are valueless (e.g. paint finish on bicycle frames). Insignificant characteristics are also removed. They are those characteristics which do not vary significantly or those for which the overall contribution to utility is small. Aggregable characteristics are converted into a common metric scale (e.g. service life incorporates many mechanical properties of a part, while cost reflects the ease of manufacturing and raw materials expenses). Finally, intangible characteristics are removed from consideration. These characteristics have origins which are incompletely

understood and are not measured in a consistent or standardized manner. The remaining relevant characteristics are traded-off. Improvements in performance over a specified range of validity are desired and valuable to the designer.

2. Utility Estimation: The relative value of the independent characteristics alone and in combinations are next determined. This is done through a personal interview, lasting about an hour, with the individual responsible for choosing production design specifications. The questionnaire used to interview the frame manufacturers is found in Appendix B.

During the interview, the selector is presented with uncertain situations called lotteries. The questionnaire used with ATB manufacturers is based on a type of lottery called a probability equivalent. The probability equivalent lottery is shown schematically in Figure 5-1. The selector is presented with the choice between a certain situation A, and the lottery of B and C as defined by the probabilities p and 1-p.



where "~" indicates indifference

Figure 5-1: Schematic of the Probability Equivalent Lottery.

Through successive questioning, the probability p is determined which makes the lottery as attractive as the certain value. This point of indifference is used to write an identity in utility which relates the utility of A to the utilities of B and C:

$$U(A) = p \cdot U(B) + (1 - p) \cdot U(C)$$

where:

$U(X)$ symbolizes the utility of X.

The probability equivalent method can present problems of accuracy (de Neufville and McCord, 1986, pp. 56-60, Mangin, 1993, pp. 172-175), but was used because of its relative simplicity.

3. Data Reduction: The complicated, multi-dimensional trade-offs between the independent characteristics can be made explicit by mathematical analysis of the interview data. The utility itself is measured on a scale called the ordered metric. Two reference points are needed to define an ordered metric scale. For example, the centigrade temperature scale is an ordered metric — the normal boiling temperature and freezing temperature of water were arbitrarily set at 100°C and 0°C respectively. In MAUA, 1 is set as the MAU of the most preferred combination of the characteristics (e.g. lowest weight/lowest cost) and 0 is set as the MAU of the least preferred combination of the characteristics (e.g. highest weight/highest cost).

Specifically, the following mathematical definition of multi-attribute utility is used:

$$K \cdot U(X1,\ldots Xn) + 1 = \prod_{i=1}^{n} (K \cdot ki \cdot U(Xi) + 1)$$

where:

$U(X1,\ldots Xn)$ is the multi-attribute utility for all attributes X_i

$U(Xi)$ is the one dimensional utility function for the attribute X_i

ki is the individual scaling factor for the attribute X_i and is determined from interviewee responses

K is a normalizing parameter, defined by $K + 1 = \prod_{i=1}^{n} (K \cdot ki + 1)$

4. Utility Analysis: Based on the selector's defined preferences, the analyst can determine the utility of any combination of characteristics. This utility is called the multi-attribute utility. The material alternative with the highest MAU is preferred. For a given interviewee, MAU can only be used to determine which combination is preferred, not the magnitude of the preference. For example, a utility of 1.0 is not twice the utility of 0.5 just as 100°C is not twice as hot as 50°C.

Additionally, because cost is always a consideration, the multi-attribute utility functions also allow the analyst estimate the monetary worth of improvements in materials characteristics. More information on this technique can be found in the works referenced (de Neufville, 1990, pp. 352-429; Field, 1988; Field and de Neufville, 1988, pp. 378-382; Mangin, 1993; Ng, 1990; Thurston, 1987).

As Section 5.2 describes, MAUA was not helpful in evaluating materials for ATB frames because the bicycle industry lacks clear and objective definitions of frame performance. However, Sections 5.3 and 5.4 present the interpretation of the multi-attribute utility functions which were determined for ATB disc brake rotors and wheel rims.

5.2 Frames

In order to better understand materials selection, key persons at five frame manufacturers were interviewed personally using MAUA and additional designers and engineers were contacted by telephone. The manufacturers interviewed were Cannondale Corporation (Georgetown, CT), Fat City Cycles (Sommerville, MA), Merlin Metalworks, Inc. (Cambridge, MA), Montague Corporation (Cambridge, MA), and Trek Bicycle Corporation (Waterloo, WI). Interview data and results are shown in Appendix C. The companies ranged widely in scale and scope. For example, Trek annually manufactures and assembles about 400,000 carbon fiber reinforced epoxy, aluminum, and chromoly steel frame bicycles, while Merlin annually builds about 3000 high end titanium bicycle frames.

The companies consider physical properties which contribute to frame cost, weight, service life, stiffness, and aesthetics when selecting materials. Upon further questioning, it was discovered that the only relevant characteristics are frame weight and cost. The stiffness of the current frame is desired and tube diameters, cross-sections, and thicknesses, as well as frame geometry can be redesigned for a given material. An increased modulus is only desirable if it allows the designer to save weight or cost. Aesthetics is dependent in part on the materials ability to hold paint and in part on the final "look" of the frame. Service life is also binary. The frames are designed to outlast the desire of a normal rider to continue riding it, but an exact time cannot be assigned because it depends on the riding style of the individual. Most recreational bicyclists will never ride their bikes beyond design specifications and will enjoy many years of trouble-free use. In fact, because frame designs continue to change so significantly, some riders will actually upgrade long before their frames approach failure. There are also more radical riders who take pride in breaking their frames and constantly push their bicycles (and perhaps their bodies) to the limits. Because the latter class exists, manufacturers build weak spots into frames which fail non-catastrophically and are easy to fix. One of the manufacturers included fatigue limit strength as a separate independent characteristic, but post-interview conversations indicated otherwise.

Additional telephone interviews verified that industry-wide, frame cost and weight are the only two engineering characteristics which are traded-off. The other characteristics are important constraints which must be satisfied. However, even the objective measures of cost and weight are not sufficient to distinguish one frame from another — retail price seems most dependent on market perception. The retail prices and weights of selected ATB frames are shown in Figure 5-2. The chart demonstrates that weight is not the major factor influencing a frame's retail price; the large scatter highlights the importance of a well thought-out marketing strategy. Since there are no other relevant characteristics, retail cost must depend on marketing considerations.

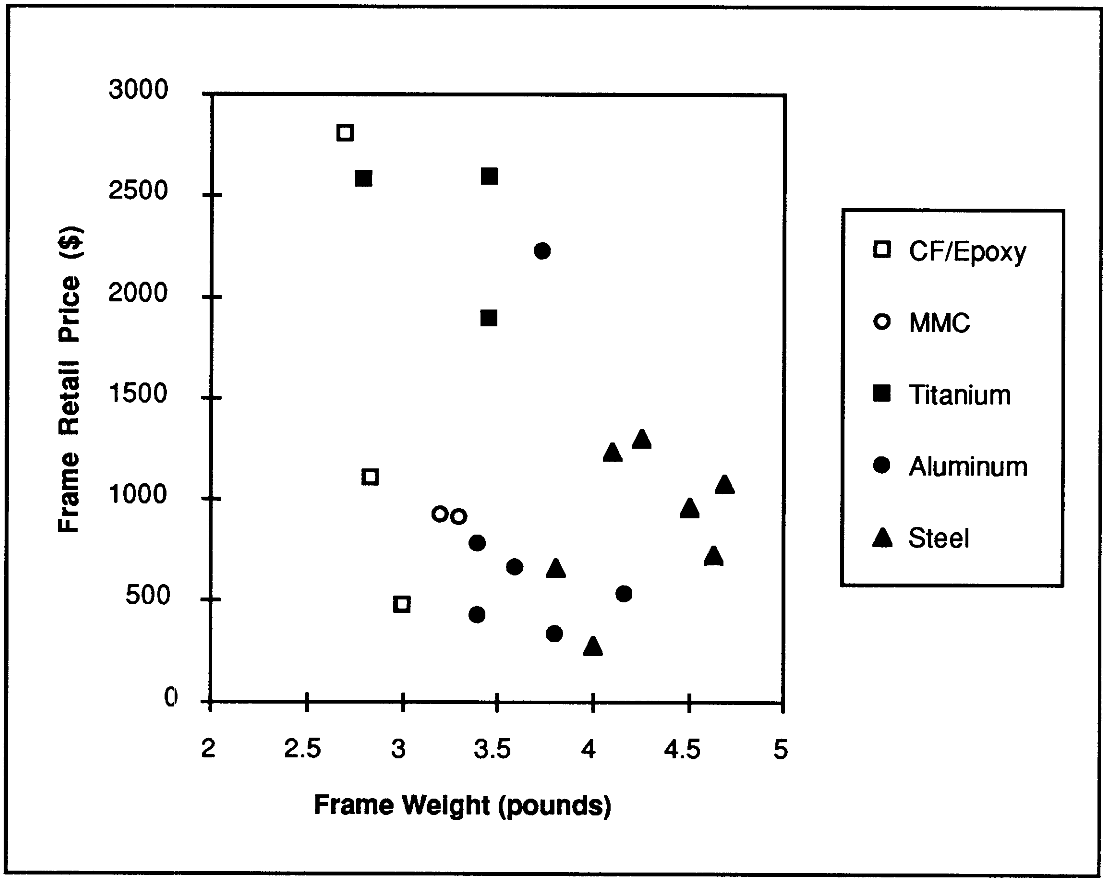


Figure 5-2: All-Terrain Bicycle Frame Weights and Retail Prices. CF/Epoxy: carbon fiber reinforced epoxy composite; MMC: ceramic reinforced metal matrix composite.

Many riders believe that certain materials and brand names are superior and they are willing to pay a premium to have "bragging rights." From a material standpoint, titanium and carbon fiber reinforced epoxy currently have this kind of marketable allure. As the largely successful efforts of Alyn and Duralcan suggest, MMCs may also have a special market appeal. Each bike maker sells to a defined market segment and the maker knows how much its customers are willing to pay for performance. Frames of some manufacturers command prices which cannot be justified by weight, or even service life, alone. The decision to introduce a new material into high end ATBs is complicated and depends on whether the manufacturer wants to replace the existing lines or increase production and risk cannibalizing traditional products. Additionally, the manufacturer must ask whether the new frames would compete in an unfamiliar market segment.

5.3 Disc Brake Rotors

Materials selection for disc brake rotors appears to be different from that for frames. Designers and engineers at several companies were contacted and Dia-Compe USA (Fletcher, NC) was interviewed personally. Dia Compe USA manufactures and distributes various high quality bicycle components including brake systems and wheel hubs. Until recently it was the U.S. division a foreign firm and it still distributes products for its former parent. Sales in 1992 for braking systems sold by Dia-Compe USA and its former parent were 3 million units. Dia-Compe USA will began production of a DMMC rotor in late Spring 1994.

When selecting materials, Dia-Compe USA considers physical properties which contribute to rotor cost, weight, service life, stiffness, elongation, surface trueness and flatness, and coefficient of friction. Only cost, weight, and service life are traded-off. The stiffness of an aluminum rotor and a minimum elongation of 8 percent are required. Trueness and flatness are related to cost. Coefficient of friction is binary. For the traded-off characteristics, the maximum cost is $15, the maximum weight is 210 grams, and a minimum service life is 3 months. Designs which fall outside these ranges are automatically rejected.

The trade-offs between performance and cost for Dia-Compe USA were determined using MAUA. From the utility function obtained, MAU values were determined for various combinations of the independent characteristics. Interview data and results are shown in Appendix C. These values were grouped and plotted as an iso-utility contour map. Dia-Compe USA's utility function as an iso-value plots is shown in Figures 5-3 and 5-4. Just as geographical contour maps use lines to join locations of equal elevation, the lines in Figure 5-3 show the combinations of rotor weight and cost which yield identical utility. Furthermore, since low weight and low cost are preferred, the utility represented by the lines increases downward and to the left. Likewise, in Figure 5-4 the lines show the combinations of rotor service life and cost which yield identical utility. Utility increases downward and to the right.

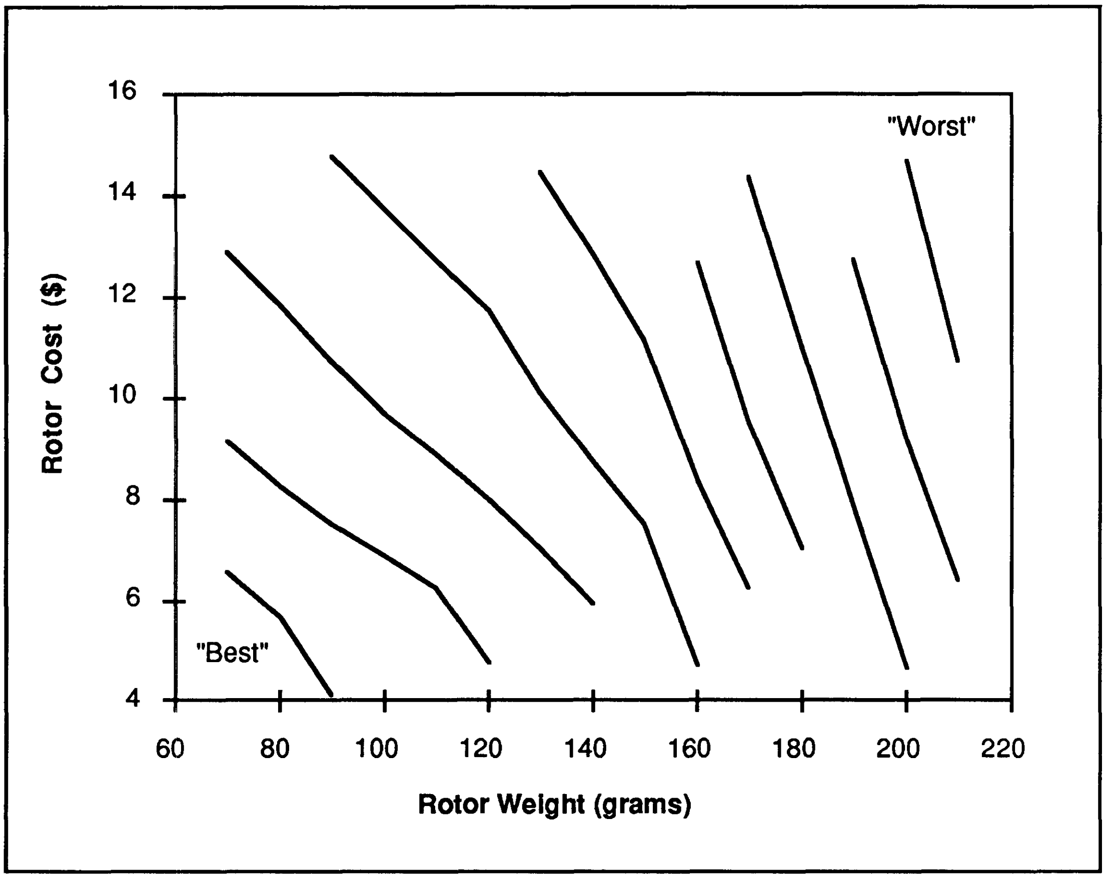


Figure 5-3: Disc Brake Rotor Weight—Cost Multi-Attribute Utility Contour Plot for Dia-Compe USA.

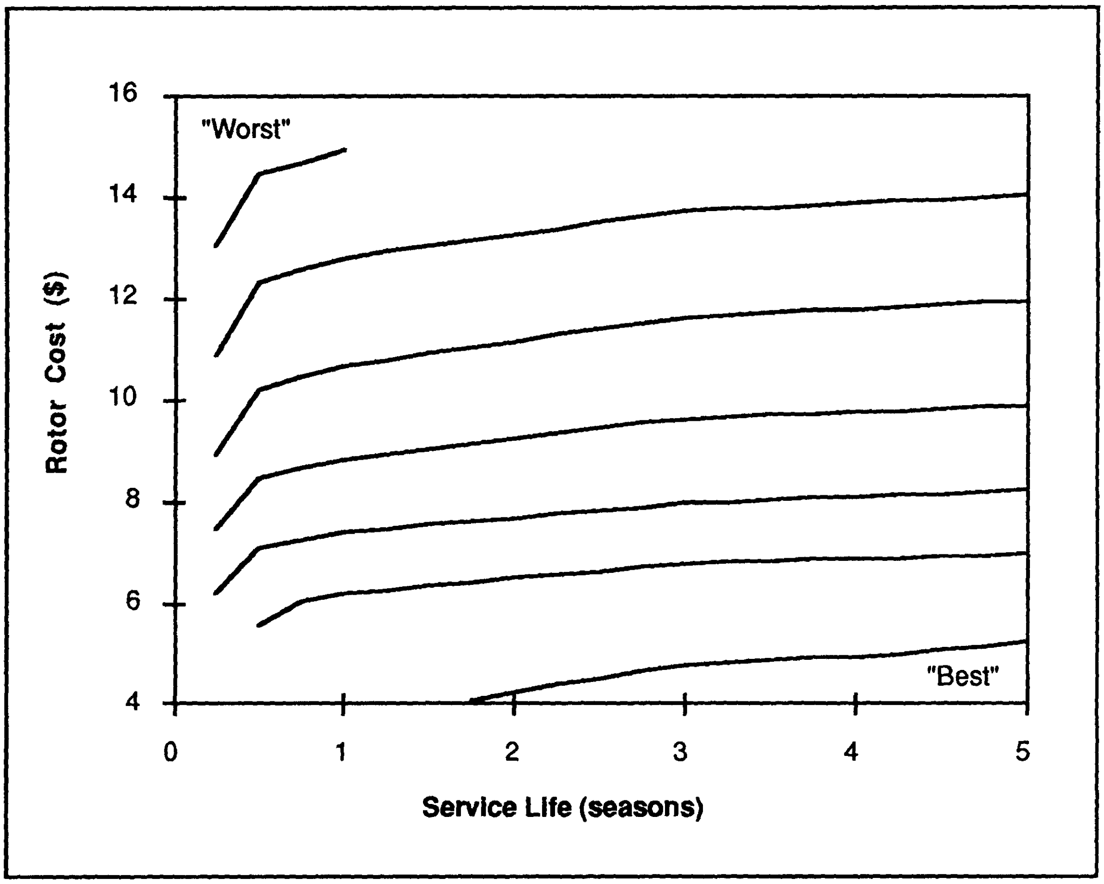


Figure 5-4: Disc Brake Rotor Service Life—Cost Multi-Attribute Utility Contour Plot for Dia-Compe USA.

The slope of the iso-utility line through any point on Figure 5-3 represents how much incremental reductions in weight are worth to the designer (i.e. how the designer trades weight off against cost). As might be expected, the relative importance changes over the range of consideration. Improvements at weights above 160 grams are worth about 39¢ per gram of weight saved, but only about 12¢ per gram saved at lower weights. This type of response is common and is consistent with the principle of diminishing marginal utility: the addition to utility accompanying each subsequent unit of weight reduction becomes smaller and the designer becomes increasingly cost conscious.

Similarly, the slope of the iso-utility line through any point on Figure 5-4 represents how much incremental increases in service life are worth to the designer. Two observations can be made. First the relative importance of service life improvements does not change significantly over the range of consideration. The designer is only willing to pay an average 8¢ to 10¢ per quarter year increase in service life. However, an improvements from a quarter year to a half year service life is worth about $1.20. The designer mentioned that this is because it would be very difficult to sell a rotor that only lastes a quarter year.

Using Figure 5-3, alternative rotors designs having identical service lives can be compared. For example, a rotor weighing 140 grams and costing $8 would be preferred to a rotor weighing 160 grams and costing $6 because the options lie on opposite sides of an iso-utility line. With the iso-utility lines as guides, any two such designs can be evaluated. Similarly, rotors of identical weight can be compared using Figure 5-4.

Dia-Compe USA's prototype DMMC rotor were compared to alternative brake rotors. The properties of these rotors are shown in Table 5-1. The stainless steel design is easy to reject because its weight is outside of the range of validity, but the aluminum rotor cannot be rejected so easily. Comparison is difficult first because the designs cannot be plotted in two dimensions and second because costs are not known. Although the aluminum rotor weighs more and has a shorter service life, one cannot determine *a priori* if an extremely low cost could compensate for these shortcomings.

Table 5-1: Disc Brake Rotor Attributes Important to Dia-Compe USA.

Attribute	**Range**	**DMMC**	**Anodized Aluminum**	**Stainless Steel**
Cost	\$4 to \$15	\$?	\$?	\$?
Weight	70 to 210 grams	120 grams	210 grams	280 grams
Service Life	0.25 to 5 years	5 years	1 years	5 years

The two rotors were evaluated directly by plotting the utility function in a different way. A rotor cost and utility plot for both designs is shown in Figure 5-5. Because MAUs can be compared directly, this figure clearly shows that the DMMC rotor would be preferred at any cost even if the anodized rotor were to cost only $4. This analysis indicates that the disc brake rotor application is excellent for DMMC because the success of the design is quite dependent on the materials properties. The high wear resistance permits a long service life, while the higher modulus and strength allow a lighter design. This disc brake system is said to be about 150 grams heavier than a cantilever brake system (Kukoda, 1993, p. 93). Consumers will decide whether the increased performance is worth the added weight and cost.

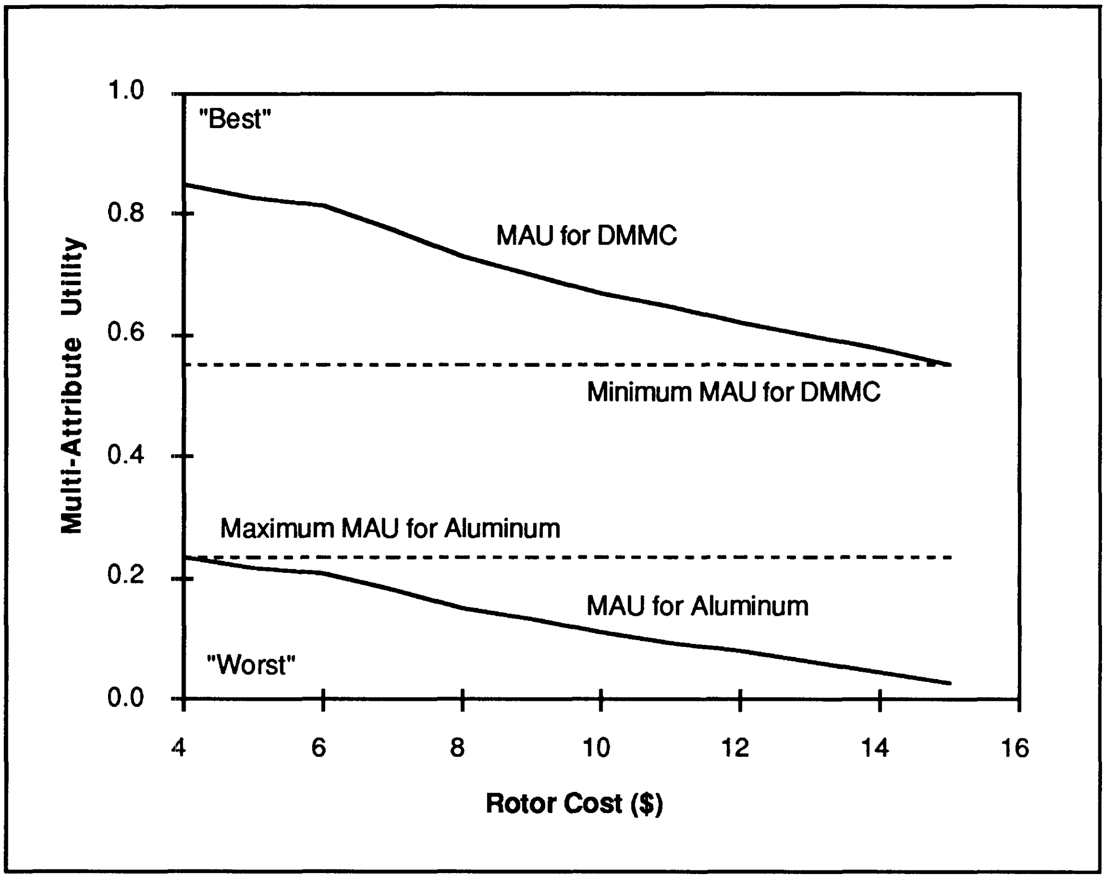


Figure 5-5: Multi-Attribute Utility Comparison between Duralcan Metal Matrix Composite and Anodized Aluminum Disc Brake Rotors for Dia-Compe USA. MAU: multi-attribute utility; DMMC: Duralcan metal matrix composite.

5.4 Wheel Rims

Materials selection for wheel rims also appears to be based on materials characteristics. Designers and engineers at several companies were contacted and Sun Metal Products, Inc. was interviewed using MAUA. Sun is a leading manufacturer of steel and aluminum alloy wire spoke wheel rims for bicycles and wheelchairs. It serves OEM and after-market customers and had 1992 sales of 2.5 to 3 million units. Sun has made a prototype DMMC rim and is actively commercializing rims made of the material.

When selecting materials, Sun considers physical properties which contribute to rim cost, weight, service life, stiffness, elongation, and aesthetics . Only rim cost, weight and service life are traded-off. Current rim stiffness is desired and an elongation of 8 percent is required. Aesthetics predominately refers to the ability to anodize rims — not a deciding factor because most ATB rims are made of aluminum. The service life utility is measured relative to aluminum. For example, the designer estimated that for a given rim weight, a DMMC rim could last twice as long as an aluminum rim. The absolute service life in years also depends on the amount of material which can be worn away before failure occurs; for a given material type, a heavier rim design has a longer absolute service life. Therefore, a Duralcan MMC can be used either to increase the absolute service life of a particular rim design or to decrease weight and maintain the same absolute service life for a new rim design. For the traded-off characteristics, the maximum cost is $25, the maximum weight is 500 grams, and a minimum service life is a 10% decrease relative to aluminum. Designs which fall outside these ranges are automatically rejected.

The trade-offs between performance and cost for Sun were determined using MAUA. Interview data and results are shown in Appendix C. Sun's utility function as iso-value plots is shown in Figures 5-6 and 5-7. The lines in Figure 5-6 show the combinations of rim weight and cost which yield identical utility. Low weight and low cost are preferred, so the utility represented by the lines increases downward and to the left. In Figure 5-7, the lines show the combinations of rim service life and cost which yield identical utility. Long service life and low cost are preferred so utility increases downward and to the right.

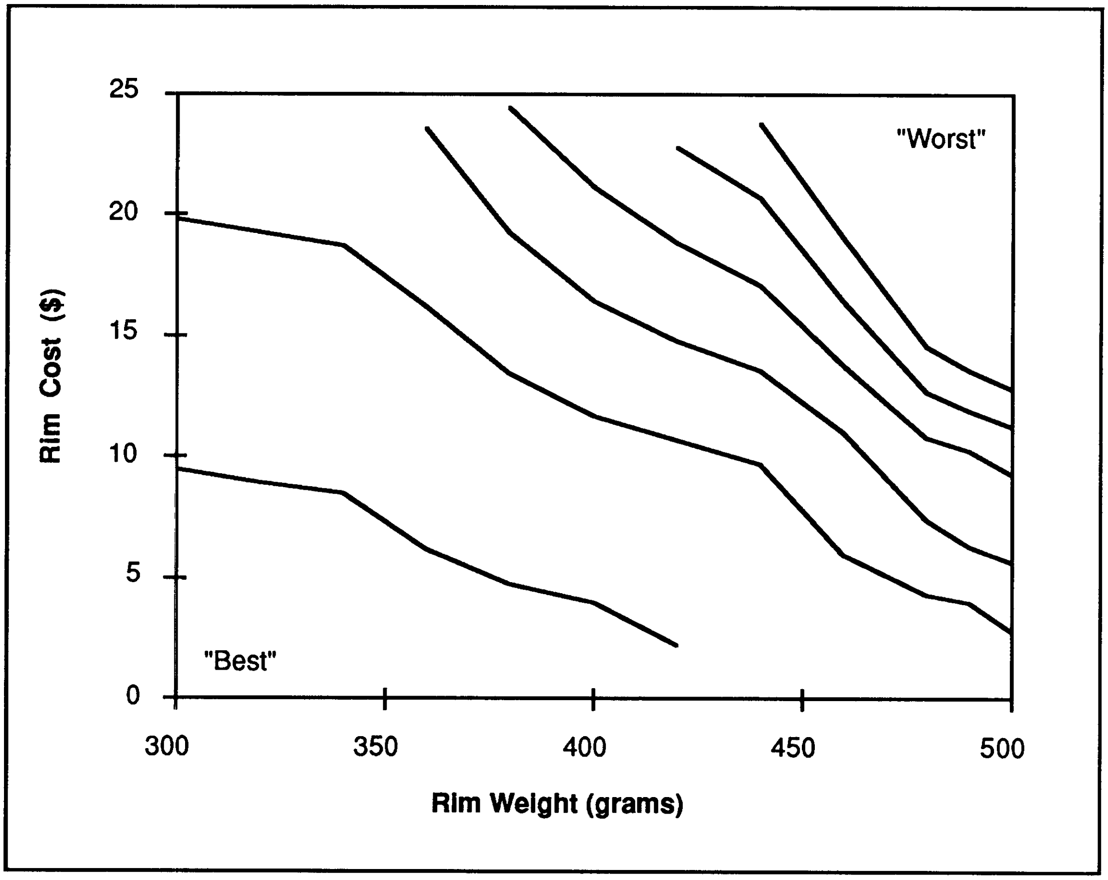


Figure 5-6: Wheel Rim Weight—Cost Multi-Attribute Utility Contour Plot for Sun Metal Products, Inc.

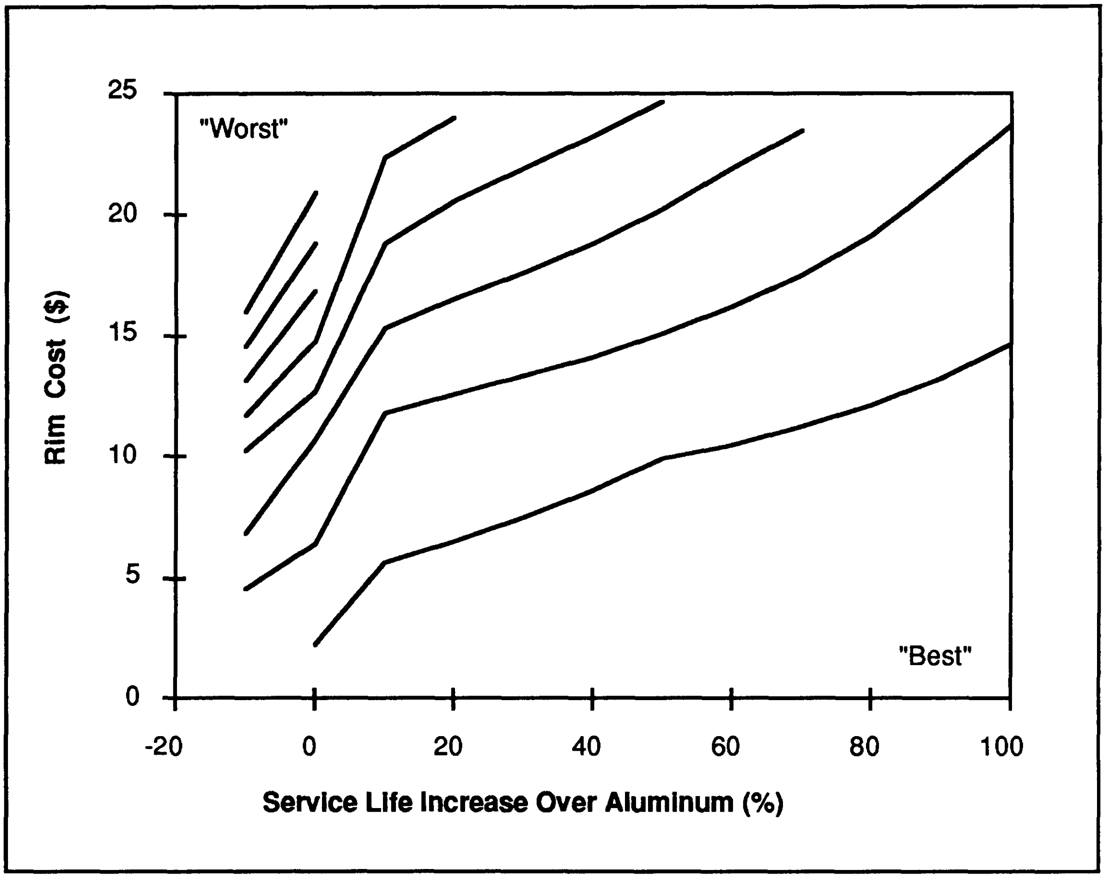


Figure 5-7: Wheel Rim Service Life—Cost Multi-Attribute Utility Contour Plot for Sun Metal Products, Inc.

The worth of incremental reductions in weight can be calculated from the slope of the iso-utility line through any point on Figure 5-6. The relative importance varies over the range of consideration. Improvements at weights above 450 grams are worth about 10¢ per gram of weight saved, but decrease in value to about 3¢ per gram saved at lower weights. In Figure 5-7, the relative importance of cost and service life also changes. Improvements at shorter service lives (less than a 10% increase over aluminum) are worth about 40¢ per percent improvement and only about 13¢ per percent improvement at longer service lives.

Sun's prototype Duralcan rim can be compared to another aluminum rim of equal weight. The properties of these rims are shown in Table 5-2. Because the costs are not known, the designs must be compared using a cost versus utility graph. As with the rotors, the question becomes whether a low cost could compensate for the shorter service life of the aluminum rim. A rim cost and utility plot for both designs is shown in Figure 5-8. This figure shows that the DMMC rim would be preferred to aluminum under certain cost situations. Duralcan must price its material so that the MAUA for DMMC is higher than that of aluminum.

Table 5-2: Bicycle Rim Attributes Important to Sun Metal Products, Inc.

Attribute	**Range**	**DMMC**	**Aluminum**
Cost	\$2 to \$25	\$?	\$?
Weight	300 to 500 grams	420 grams	420 grams
Service Life	-10% to 100% increase over aluminum	100% increase over aluminum	0% increase over aluminum

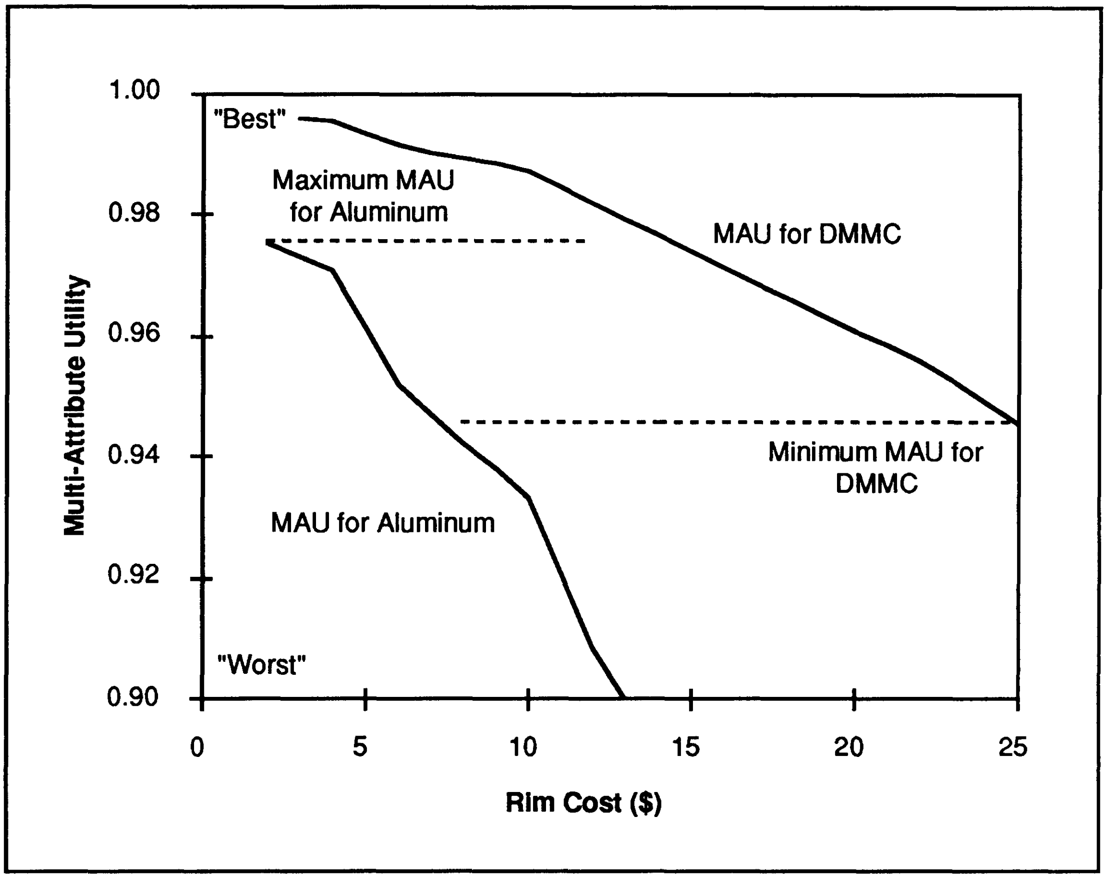


Figure 5-8: Multi-Attribute Utility Comparison between Duralcan Metal Matrix Composite and Anodized Aluminum Wheel Rims for Sun Metal Products, Inc.
MAU: multi-attribute utility; DMMC: Duralcan metal matrix composite.

6.0 Policy Analysis and Recommendations

6.1 Introduction

Because of its unique combination of cost and performance, DMMC is likely to be appropriate for applications in many manufacturing industries. The main problem faced by Duralcan is that all viable applications cannot be identified, let alone supported, through marketing efforts. As Section 1.2 states, it is proposed instead that Duralcan identify and help commercialize a few showpiece applications.

This thesis focuses on the policy faced by Duralcan in marketing DMMCs to the manufacturers of ATB applications with the intention of encouraging the material's adoption by large-scale users. More specifically, the central goal of this research was to identify the combination of performance and price which Duralcan has to offer before DMMC is incorporated into designs for ATB frames and components.

6.2 Policy Framework for Marketing Engineering Materials to Manufacturing Firms

As Section 2.1 discusses, there are several reasons the supplier of a new material may want to work with responsive niche customers while future large-scale customers prepare for production. The benefits of so doing include generating positive cash flows, reducing costs through learning and experience, smoothly increasing production volumes to meet future demand, building and strengthening working relationships with fabricators, and developing name recognition.

Section 2.2 suggests that certain customers are fast adopters of materials because they make design changes frequently and because they expect significant gains from the substitution of new materials. It is reasonable to assume that manufacturers in fast growing industries should be quick to adopt and commercialize new materials. These industries probably have products for which designs are not yet standardized so materials with improved properties are actively sought. Rapid growth normally implies lower price sensitivity — an important point since new materials are often more costly.

In developing a market for new materials, Section 2.3 emphasizes that the supplier must *both* build a strong fabricator network *and* stimulate manufacturer demand. Implicit to this dual role was the choice of a marketing focus, both in terms of level (e.g. fabricator versus manufacturer) and potential adopter (e.g. market leader versus growing firm). A discussion of innovation diffusion research was presented to give insight into the methods of encouraging the adoption process. Research suggested that information concerning the material should be presented according to the individual's needs. More importantly, it indicated that the form of this information (e.g. property data versus materials samples) changes with the customer's stage in the adoption process.

Underlying successful marketing of advanced materials is an understanding by the supplier of how potential customers select materials. Unless this insight is obtained, resources wasted through incorrect packaging of the material in terms costs, properties, and availability. A poor appreciation of the potential customer's needs may even discourage adoption if the supplier is seen as being indifferent. As discussed in Section 5.1, MAUA is useful in making the selection process explicit. For a specific application, MAUA helps the materials supplier determine

- Materials selection constraints
- Traded-off characteristics and their ranges of validity
- Relative nonlinear weighting factors for performance characteristics
- Materials which are preferred by a selector for a given design
- Changes in the characteristics of an inferior material necessary for a preference change to occur

MAUA allows a supplier to target marketing efforts and to identify applications which would serve as excellent showpieces.

6.3 Marketing Duralcan Metal Matrix Composites to the All-Terrain Bicycle Industry

6.3.1 Policy Analysis for All-Terrain Bicycle Frames, Disc Brake Rotors, and Wheel Rims

Firms serving the bicycle industry were identified as promising interim customers for DMMC since they adopt new materials quickly and do so into high margin products. Although bicycles predate automobiles, the bicycle industry is in many ways inexperienced and lacks a high degree of technical sophistication. The recent influx of new materials has undoubtedly led to product improvements, but designs are often not optimized for a given material. Most designers do not have the empirical data necessary for realistic computer models so prototype analysis is often most helpful.

If additional frame customers are desired, it appears that DMMC may be helpful to manufacturers of aluminum frames. First, although raw material and processing costs will be higher, improved mechanical properties may permit frame weight reduction. For example, manufacturers must increase aluminum tube diameters to obtain sufficient strength and stiffness, but the limited tire clearance around the seat and chain-stays of traditional frames can force design sacrifices. The increased modulus of DMMC would permit the use of thinner tubes and allow for a lighter overall frame. Additionally, uneven terrain causes the chain to contact and wear the right chain-stay so DMMC's high wear resistance would be beneficial.

The marketable allure of MMCs may be attractive to those high-end manufacturers of steel, aluminum, or titanium frames that are looking to reinforce their high-tech image. Existing infrastructure and experience would allow these firms to produce another "elite" frame with only limited investment in manufacturing equipment and processing skills.

As Section 5.2 discusses, MAUA interviews for frames indicate that only weight and cost are traded-off. However, even these two objective characteristics are not sufficient to predict materials selection. It seems that while a minimum property levels exist, performance is difficult to define and even harder to measure — materials are chosen largely on the basis of subjective factors and marketing considerations.

Despite the non-objective materials selection observed, frames are currently the largest volume application in the ATB industry of MMCs generally, and of DMMC specifically. These frames are competitive with, but not superior to, those made of other materials. This marketing concern does not mean that Duralcan should not market to frame makers, but instead suggests that commercial success of DMMC cannot be easily linked to materials properties. Frames may not make good showpieces for large-scale adopters. As Section 5.2 notes, MAUA was not conducted for fully-suspended frames. The improved strength and high modulus of DMMC may be highly valued for this application.

If Duralcan's goal is encourage material diffusion, resources should be applied preferentially to support products for which a clearer link exists between the properties of DMMC and the requirements of the application. For the disc brake rotor and the wheel rim, MAUA has shown that DMMC is preferred to other materials. Performance measures for these applications are established and selection is based on objective trade-offs between cost, weight, and service life. From the selector's perspective, the high wear resistance and low density of DMMC justify a cost premium.

6.3.2 Competitive Threats to Duralcan Metal Matrix Composites from Other Materials for All-Terrain Bicycle Applications

As Section 4.2 mentions, DMMC and Boralyn have been used successfully in ATB frames. Other aluminum MMC frames will soon be available. Advanced Composite Materials Corporation (ACMC) will offer one called SXA with SiC whisker reinforcement (Advanced Composite Materials Corporation, 1994). In 1994, frames by American Bicycle Manufacturing, Clark Kent, Dean Ultimate Bicycles, HH Racing, and Sampson Sports will feature SXA (Kukoda, 1993, pp. 91-92). DWA Chatsworth, a composites division of British Petroleum, will supply Raleigh with an aluminum matrix/SiC composite for a new ATB (Kukoda, 1993, p. 92). Raleigh previously used the material for its top road bike (Levin and McConnell, 1993, pp. 44-45; "Steel Alternatives," 1993, p. 4).

Although many different MMCs exist, the two important advantages of DMMC are its low cost and its availability in large commercial quantities (Schuster, 1993, p. 343). As discussed, frame applications do not have defined performance criteria and bicyclists are willing to pay high prices for perceived quality. This combination makes it quite conceivable that DMMC could become commonplace for frame applications. Others will be able to justify the higher costs of their MMCs through marketing efforts. Duralcan should carefully consider the competition from other MMCs when developing its strategy for ATB frames.

Materials decisions for the two components studied appear to be based on well defined performance characteristics, so competition from other MMCs should not be significant. The selectors at Dia-Compe and Sun Metal both stressed that the costs of other MMCs were prohibitive.

Disc brakes offer many advantages for ATB use and they are likely to increase in popularity. Rim manufacturers could respond by redesigning rims to be lighter since wear resistance and heat dissipation are no longer critical. The rim would no longer serve as a braking surface so one could ask whether aluminum and DMMC would remain materials of choice. Although not explicitly considered, this case warrants further examination.

The polymer composite spoke wheel is another development which could affect demand for DMMCs. These wheels are strong, aerodynamic, and low maintenance, but expensive. Specialized/Du Pont and GT/Innovations in Composites both offer 3-spoke, one-piece composite wheels bonded to aluminum rims and hubs (Hopkins, et al, 1990, p. 956; Kukoda, 1993, p. 95). DMMC should be attractive for this application if rim brakes are used.

6.3.3 Recommendations for Continued Marketing Efforts in the All-Terrain Bicycle Industry

Based on the research conducted for this thesis, the following recommendations are made to Duralcan as it further develops its strategy for marketing DMMC to the ATB industry.

- Provide commercialization assistance to manufacturers of disc brake rotors and wheel rims. This should include technical and design support as well as help in partnering with fabricators. The wear resistance and low density of DMMC are clearly beneficial, so commercial success of these applications would promote diffusion and adoption by users in both niche and large scale industries.

- Reconsider the marketing strategy for frames. Increased competition from other MMCs and the lack of design requirements make this application questionable.

- Study the required materials characteristics for fully suspended ATB frames further. The increased stiffness of DMMC may be advantageous for whole frames or for certain structural sections thereof.

- Encourage manufacturers using DMMC to advertise the material source clearly; references to Duralcan help to develop material name recognition. Although the Specialized ATB made of DMMC is a commercial success, many know the material only by Specialized's trademarked name, M2. As materials like Teflon and Kevlar suggest, the manufacturer also gains consumer confidence when a material has a high quality image.

- Identify additional applications where DMMC's low cost, increased stiffness, and high wear resistance are beneficial. Other ATB components could include sprockets (free-wheels and chain-rings), suspension and brake stiffeners, front hubs, cranks, and brake levers.

- Offer information to the industry by direct mail and phone contact as well as by attendance at bicycle shows and races. This information should include technical specifications and materials properties. Duralcan should let manufacturers know that high quality MMC is available in large quantities. For example, many companies contacted with believe that the material is supplied exclusively to Specialized.

- Do not support additional applications for which DMMC cannot be justified objectively. Inferior products in the market could damage DMMC's growing reputation.

7.0 Conclusions

This thesis focused on the policy Duralcan should follow to market DMMCs to manufacturers in the ATB industry. Non-standardized products, short product cycles, expanding markets, and high profit margins encourage manufacturers of ATB applications to search for and rapidly adopt advanced materials.

The successful marketing of an advanced material like Duralcan requires that the supplier understand the way potential customers select materials. MAUA was especially helpful in making selection processes explicit. Relevant materials characteristics were identified, decision making processes used by selectors were mathematically described, and alternative material choices were evaluated.

Only weight and cost are traded-off for ATB frames. However, even these two objective characteristics are not sufficient to predict materials selection. It seems that while minimum property levels exist, performance is difficult to define and even harder to measure. Materials are chosen largely on the basis of subjective factors and marketing considerations. The commercial success of a new material cannot be easily linked to its properties.

Nevertheless, the marketable allure of MMCs may be attractive to those high-end manufacturers of steel, aluminum, or titanium frames that are looking to reinforce their high-tech image. Additionally, DMMC's increased modulus could permit the use of thinner diameter tubing and thus yield weight reductions, and DMMC's excellent wear properties could decrease chain-stay wear by the chain. MAUA was not conducted for fully-suspended frames, but the improved strength and high modulus of DMMC may be highly valued; suspension components would ensure the comfortable ride of an otherwise stiff frame.

If Duralcan's goal is to encourage material diffusion, resources should be applied preferentially to support products for which a clearer link exists between the properties of DMMC and the requirements of the application. Performance measures for disc brake rotors and wheel rims are established and selection is based on objective trade-offs between cost, weight, and service life.

For Dia-Compe USA, the rotor manufacturer interviewed, DMMC is preferred at all costs up to the designer's cost limit of $15 per manufactured rotor. The disc brake system offers better braking performance than traditional rim brakes, but the customer must accept a higher cost and weight. Dia-Compe's system adds about 150 grams to the complete bike compared with a cantilever braking system.

For Sun Metal Products, Inc., the rim manufacturer interviewed, DMMC is preferred over a wide cost range up to $25 per manufactured rim depending on the cost of an aluminum rim. In other words, DMMC is not preferred at all costs and final specification will depend on the costs of alternative rims.

Appendix A Abbreviations

Table A-1: Abbreviation Meaning List

Abbreviation	Meaning
ACMC	Advanced Composite Materials Corporation
Al_2O_3	aluminum oxide
ATB	all-terrain bicycle
B_4C	boron carbide
DMMC	Duralcan metal matrix composite
IBD	independent bicycle dealer
MAU	multi-attribute utility
MAUA	multi-attribute utility analysis
MMC	metal matrix composite
MTB	mountain bike
OEM	original equipment manufacturer
SiC	silicon carbide

Appendix B Bicycle Frame Questionnaire

Introduction

This questionnaire is designed to explore, briefly but quantitatively, your preferences for different characteristics of materials. The procedures implicit in this questionnaire have been validated in theory and in practice.

In particular, the questionnaire is a preliminary exploration of the factors leading to the selection of a material (steel, aluminum, MMC, titanium, etc.) for a particular application. We recognize that the purview of this questionnaire is limited and we encourage you to comment and advise us of any apparent limitations.

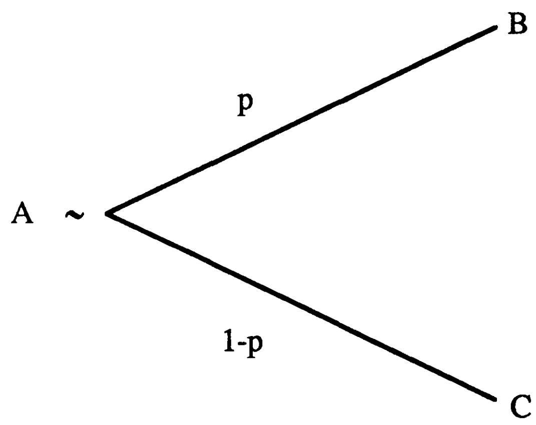
Audience

This questionnaire is directed toward a bicycle design engineer responsible for choosing a production specification for a bicycle part; in this case, a frame. By a production specification we mean the list of engineering performance criteria used to accept or reject a fabricated part for use.

This questionnaire is designed help us understand your expert professional judgment. As such, there are no right or wrong answers to questions. Rather, through your answer to these questions, we hope to outline how you trade-off different characteristics about materials.

Technical Note

The quantification of the intensity of your preferences is based upon specific questions regarding your preference between certain events (A) and uncertain situations. The uncertain situations are defined as lotteries with two possible outcomes: one outcome (B) with probability p, where p is less than 1; and a second outcome (C) with the complementary probability of occurrence (1 - p). Graphically, the uncertain situation is shown as:

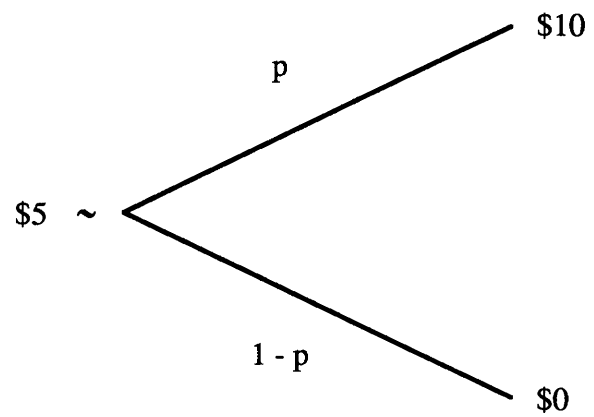


where "~" indicates indifference

We recognize that by expressing decision situations in this way we are asking you to react to an artificial problem. However, please bear with us and try to answer the questions as completely and as thoroughly as you can.

Before we talk about bicycle frames, let's try a simpler problem to familiarize you with the technique we will be using.

Imagine you have a lottery ticket that offers a known probability (p) of winning a \$10 prize. Suppose someone offers to buy this ticket from you for \$5. How low would the probability of winning \$10 have to be before you would sell this lottery ticket?



p	95%	5%	90%	10%	80%	20%	%
YES							
NO							

What is the lowest probability (p) that would cause you to sell your lottery ticket for \$5?

Bicycle Frames

We have selected several characteristics which we believe are taken into consideration when designing bicycle frames. These characteristics are:

RELEVANT?

	YES	NO
1. Cost		
2. Weight		
3. Stiffness		
4. Service Life*		

5. Other(s):

____

____

* Service life is a function of properties such as fatigue-limit strength, ultimate tensile strength, toughness, wear resistance, corrosion resistance, fatigue resistance, and impact resistance. Please note if you consider one or more individually.

Like so much of this questionnaire, this list is a preliminary one. We are very interested in your opinions so if you think that some of the listed characteristics are irrelevant to the decision or cannot be quantified, please let us know. Additionally, if there are characteristics which you believe should be included, please add them to the list. For example, how do you evaluate manufacturing flexibility (in frame design and frame size), aesthetics (initial appearance and resistance to cosmetic damage, e.g. scratches) and marketability?

Before we talk about how uncertainty affects your choice of characteristics, let's set up some basic parameters.

- First, in what terms or units do you think about these characteristics? Are these the units used when making a decision among several alternative materials?
- Next, what are the average values for your traditional material?
- What is the best possible value of these characteristics that you have observed? What is the worst possible value?

Characteristic	How measured	Average	Best	Worst
Cost				
Weight				
Stiffness				
Service Life				
Other				
Other				

We would also like to explore the degree to which the values of one characteristic influence your attitudes. Depending upon the situation, the values of characteristics may affect the way that you rank materials.

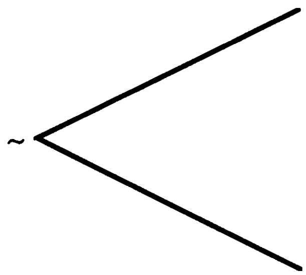
For example, your snack-fruit preference is likely to be independent of price. If you prefer an apple that costs 50¢ to an orange that costs 50¢, it is likely that you would also prefer an apple that costs $1 to an orange that costs $1. This means the price characteristic does not change your fruit preference.

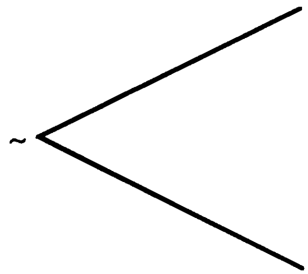
We would like to know whether the values of cost, weight, stiffness, or service life influence the preferences indicated by you for the other characteristics.

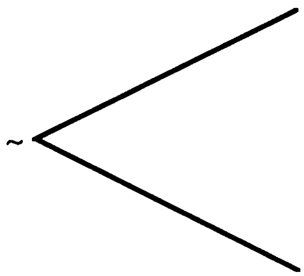
Question 1

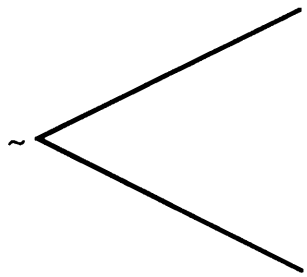
Suppose that you must prepare a material specification for a bicycle frame. You have complete freedom to specify the material to be used and the performance required of the frame as produced. Your materials testing staff has been studying a new series of materials which one of your suppliers has been promoting quite heavily. These materials, members of a series named Vitalum, are being considered as possible substitutes for your traditional frame material. Frames produced with the traditional material, TradMat, exhibit average characteristics, as described by you above. Your job is to consider the situations where the Vitalum series material is preferred over the traditional material.

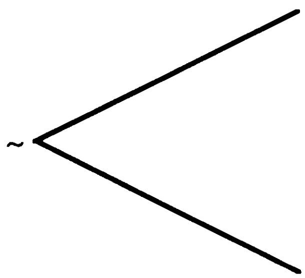
You know that the frame, when made of the traditional material, exhibits average stiffness. The engineering department feels that a frame made with Vitalum-1S will perform exactly the same as a traditional frame, except for stiffness. Based upon test results, they conclude that there is a probability (p) that the Vitalum-1S frame will exhibit an improvement in stiffness and a complementary probability (1-p) that the Vitalum-1S frame will exhibit a reduction in stiffness, as measured against the traditional frame.

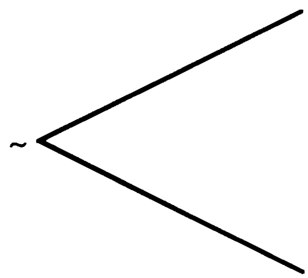






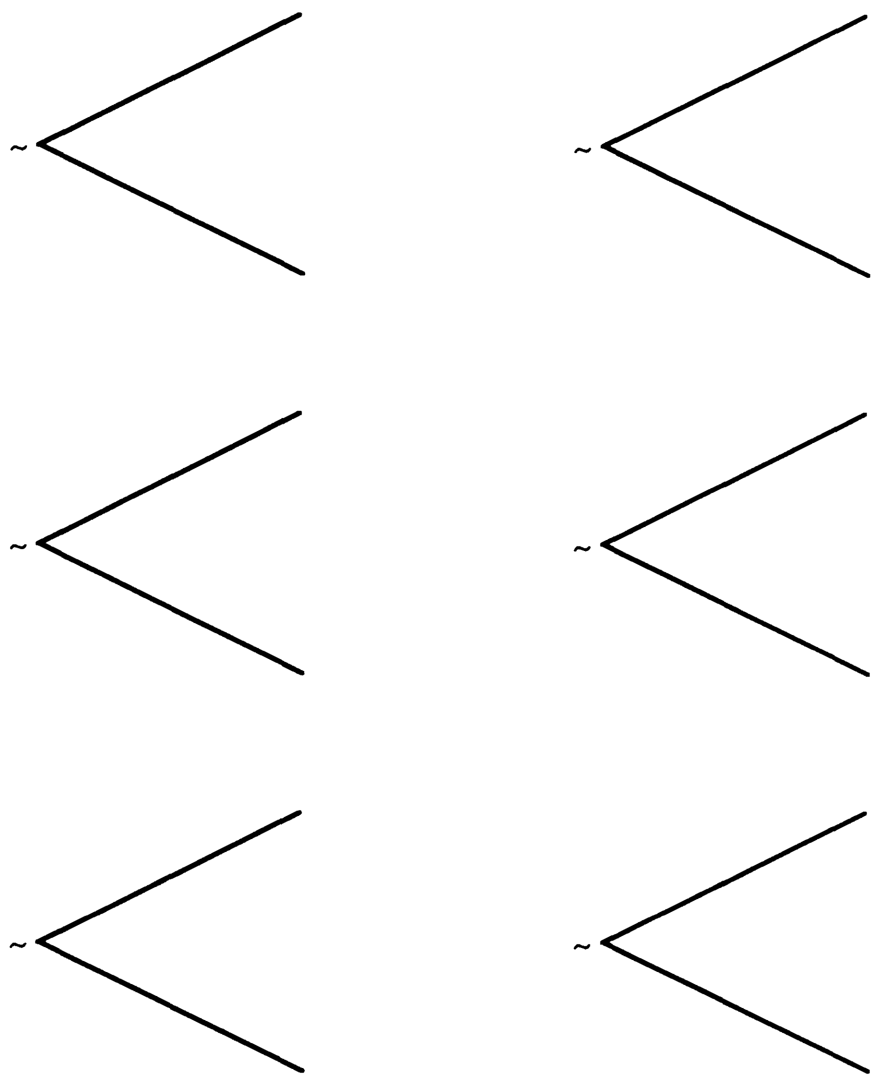






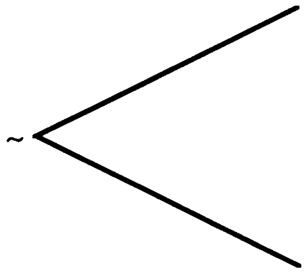
Question 2

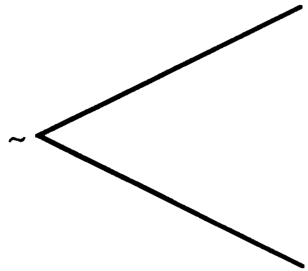
The materials department has found that Vitalum-2C behaves just the same as the traditional material in frame applications. However, the production staff has indicated that fabrication of frames with Vitalum-2C will require new processing techniques. The cost of employing these techniques may lead to a reduction in the cost of fabricating frames. However, there is a complementary probability that Vitalum-2C frames will cost more to fabricate.

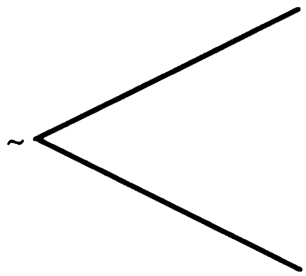


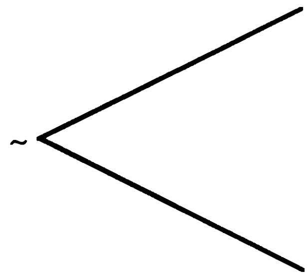
Question 3

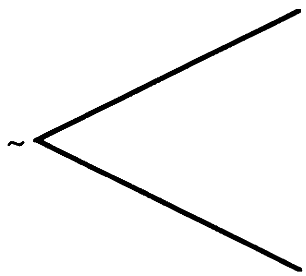
Vitalum-3W has presented a particular problem. Tests have indicated that the material exhibits structural properties identical to those of TradMat, but the samples received by your staff had a wide range in material density. Your production staff is therefore uncertain about the weight of finished frames made of Vitalum-3W. Based upon their tests, the materials staff estimates that there is a probability (p) that frames made of Vitalum-3W will weigh less than traditional frames, however, there is a probability (1-p) that the frame will weigh more than traditional frames.

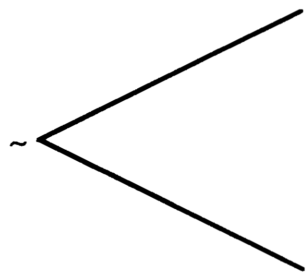






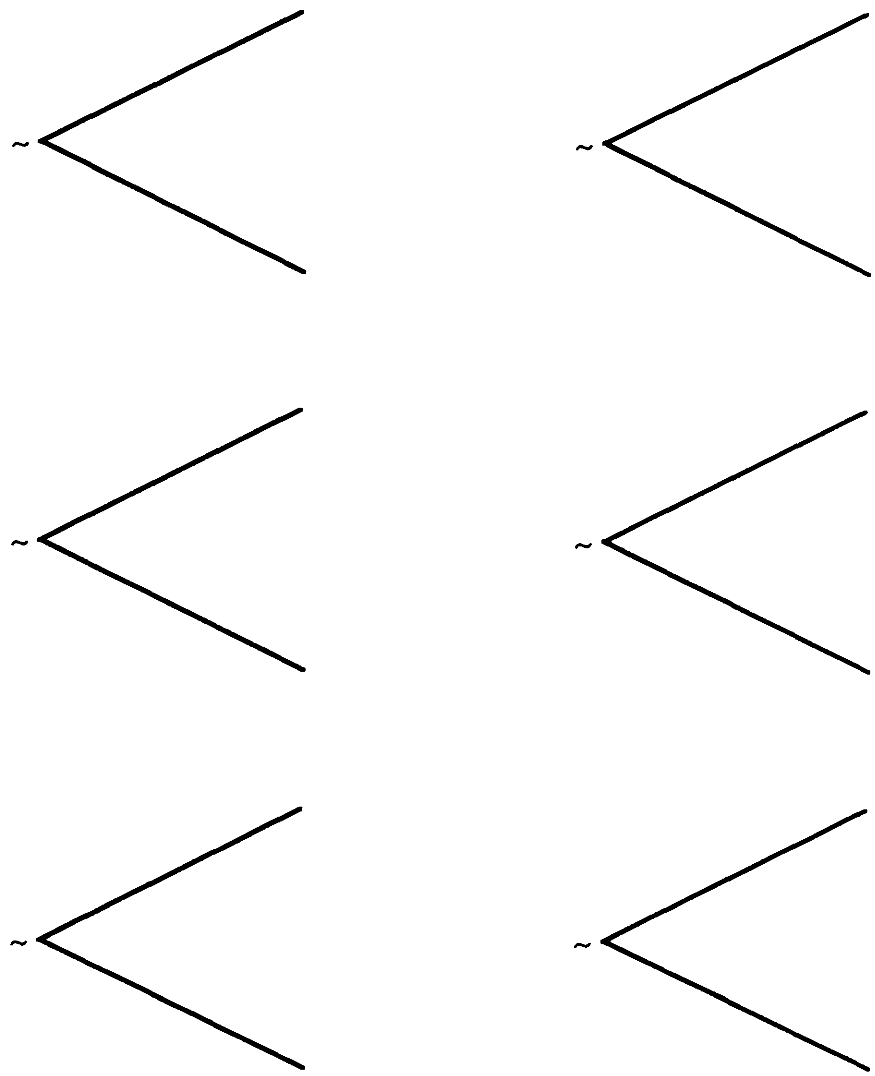






Question 4

Your materials department reports that Vitalum-4L, when used to fabricate frames, may offer improvements in service life while retaining the same characteristics in all other respects. They report that there is a probability (p) that frames made of this material will yield an improvement in service life, however, there is also a probability (1-p) that the frames will actually display a decrease in service life.

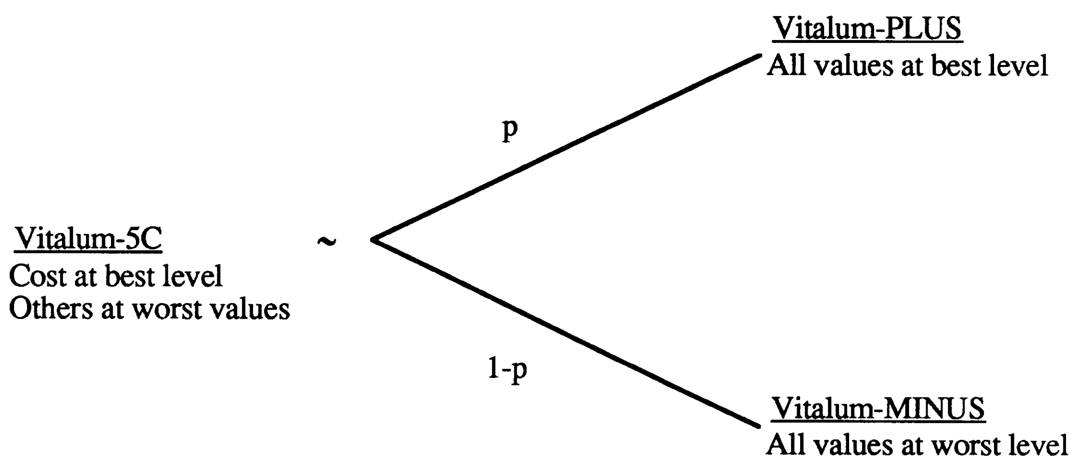


Question 5

Faced with this proliferation of Vitalum materials, you have asked the materials department to develop a new way of describing the results of their testing procedures. In light of the uncertainties that they have experienced, they have devised the following approach. They will assign a probability (p) that each material they test will behave like a hypothetical material, Vitalum-PLUS. As compared to the traditional material, frames composed of Vitalum-PLUS exhibit improvements in stiffness, cost, weight, and service life. Alternatively, the probability (1-p) will be the likelihood that the material will behave like Vitalum-Minus. Frames composed of this material exhibit decreased performance for all characteristics.

The results of a new test series on a shipment of Vitalum-5C have just been delivered to you. Vitalum-5C is advertised as a material with lower fabrication costs, but a decrease in stiffness, weight, and service life performance. However, there is a probability (p) that Vitalum-5C will behave like Vitalum-PLUS and a probability (1-p) that the material will behave like Vitalum-MINUS.

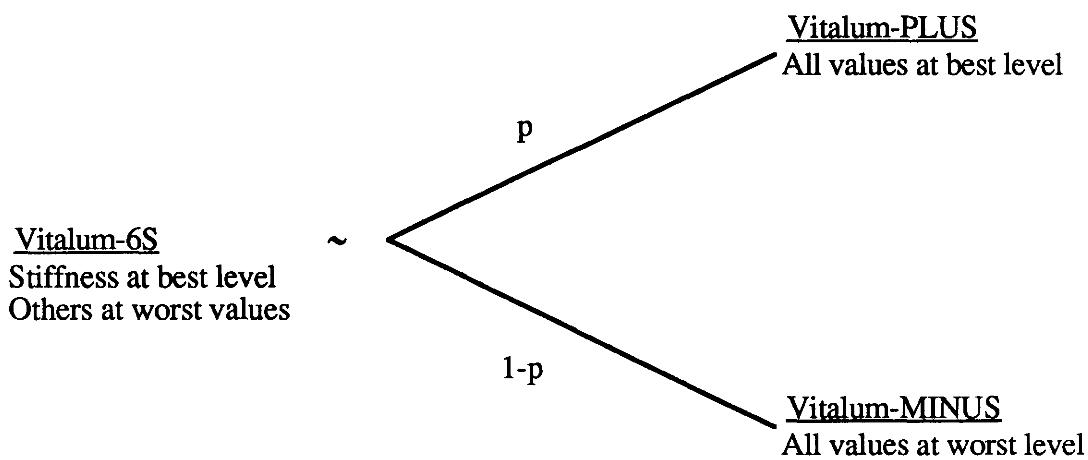
For what value of p would you prefer to use the current shipment of material instead of returning the shipment and demanding that the manufacturer satisfy its advertised claims?



Question 6

The results of a new test series on a shipment of Vitalum-6S have just been delivered to you. Vitalum-6S is advertised as a material which exhibits an improvement in stiffness, but the cost, weight, and service life performance of the material are worse than the traditional frame material. There is a probability (p) that Vitalum-6S will behave like Vitalum-PLUS and a probability (1-p) that the material will behave like Vitalum-MINUS.

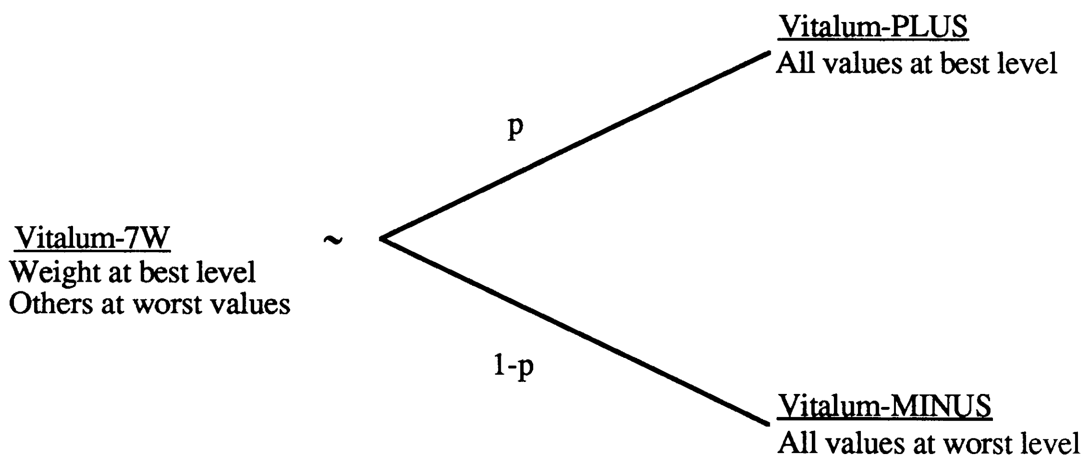
For what value of p would you prefer to use the current shipment of material instead of returning the shipment and demanding that the manufacturer satisfy its advertised claims?



Question 7

The results of a new test series on a shipment of Vitalum-7W have just been delivered to you. Vitalum-7W is advertised as a material which exhibits a reduction in weight, but the cost, stiffness, and service life performance of the material are worse than the traditional frame material.

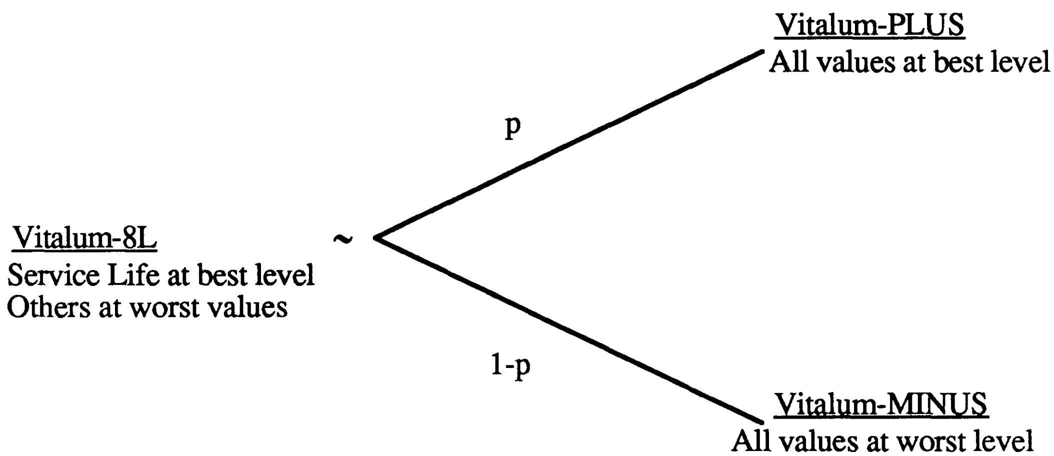
For what value of p would you prefer to use the current shipment of material instead of returning the shipment and demanding that the manufacturer satisfy its advertised claims?



Question 8

The results of a new test series on a shipment of Vitalum-8L have just been delivered to you. Vitalum-8L is advertised as a material which exhibits an improvement in service life, but the cost, weight, and stiffness performance of the material are worse than the traditional frame material.

For what value of p would you prefer to use the current shipment of material instead of returning the shipment and demanding that the manufacturer satisfy its advertised claims?



Appendix C Utility Measured Data and Results

C.1 Introduction

As Section 5.1 defines, MAU is calculated from the expression:

$$K \cdot U(X1,\ldots Xn) + 1 = \prod_{i=1}^{n} (K \cdot ki \cdot U(Xi) + 1)$$

where:

$U(X1,\ldots Xn)$ is the multi-attribute utility for all attributes X_i

$U(Xi)$ is the one dimensional utility function for the attribute X_i

ki is the individual scaling factor for the attribute X_i and is determined from interviewee responses

K is a normalizing parameter, defined by $K + 1 = \prod_{i=1}^{n} (K \cdot ki + 1)$

Utility functions for ATB frame, disc brake rotor, and wheel rim manufacturers were calculated using a standard spreadsheet (Clark, et. al., 1992, pp. 89-111). Alternative methods are available (Field, 1988, pp. 194-206; Mangin, 1993, pp. 351-352).

C.2 Frame Manufacturers

Each of Tables C-1 through C-5 presents the attribute ranges for one frame manufacturer, the data measured during the MAUA interview with that manufacturer, and the K value calculated from the data. Table C-1 contains the data and results for Cannondale Corporation. Table C-2 contains the data and results for Fat City Cycles. Table C-3 contains the data and results for Merlin Metalworks, Inc. Table C-4 contains the data and results for Montague Corporation. Table C-5 contains the data and results for Trek Bicycle Corporation.

Table C-1: MAUA Data and Results for Cannondale Corporation.

Cost		Weight		K
$k(Cost) = 0.93$		$k(Weight) = 0.90$		-0.991
Cost ($)	$U(Cost)$	Weight (pounds)	$U(Weight)$	
75	1	2	1	
100	0.93	2.5	0.97	
125	0.60	3	0.93	
150	0	3.5	0.46	
		4	0	

Table C-2: MAUA Data and Results for Fat City Cycles.

Cost		Weight		K
$k(Cost) = 0.73$		$k(Weight) = 0.95$		-0.980
Cost ($)	$U(Cost)$	Weight (pounds)	$U(Weight)$	
500	1	3	1	
800	0.9	3.5	0.95	
900	0.7	4.75	0.90	
1100	0	6	0	

Table C-3: MAUA Data and Results for Merlin Metalworks, Inc.

Retail Price		Weight		Fatigue Limit Strength at 10^7 Cycles		K
$k(Price) = 0.65$		$k(Weight) = 0.65$		$k(FLS) = 0.80$		-0.9693
Price ($)	$U(Price)$	Weight (pounds)	$U(Weight)$	FLS (ksi)	$U(FLS)$	
1600	1	2	1	40	0	
2000	0.95	2.5	0.90	50	0.40	
2500	0.70	3	0.35	55	0.60	
3000	0	3.5	0	60	0.80	
				80	0.97	
				100	1	

Table C-4: MAUA Data and Results for Montague Corporation.

Cost		Weight		K
$k(Cost) = 0.85$		$k(Weight) = 0.85$		-0.9689
Cost ($)	$U(Cost)$	Weight (pounds)	$U(Weight)$	
30	1	2	1	
50	0.98	4	0.95	
80	0.70	6	0.30	
150	0	7	0	

Table C-5: MAUA Data and Results for Trek Bicycle Corporation.

Cost		Weight		K
$k(Cost) = 0.25$		$k(Weight) = 0.95$		-0.8421
Cost ($)	$U(Cost)$	Weight (pounds)	$U(Weight)$	
15	1	2	1	
65	0.75	3.5	0.95	
80	0.53	7	0	
100	0			

C.3 Disc Brake Rotor Manufacturer

Table C-6 presents the attribute ranges for Dia-Compe USA, the data measured during the MAUA interview, and the K value calculated from the data.

Table C-6: MAUA Data and Results for Dia-Compe USA.

Cost		Weight		Service Life		K
$k(Cost) = 0.20$		$k(Weight) = 0.60$		$k(S.Life) = 0.05$		0.9067
Cost ($)	$U(Cost)$	Weight (grams)	$U(Weight)$	S. Life (years)	$U(S.Life)$	
4	1	70	1	0.25	0	
5	0.92	100	0.88	0.5	0.45	
6	0.88	120	0.80	1	0.60	
8	0.60	150	0.63	2	0.75	
10	0.40	210	0	3	0.90	
15	0			5	1	

C.4 Wheel Rim Manufacturer

Table C-7 presents the attribute ranges for Sun Metal Products, Inc., the data measured during the MAUA interview, and the K value calculated from the data.

Table C-7: MAUA Data and Results for Sun Metal Products, Inc.

Cost		Weight		Service Life Relative to Aluminum		K
$k(Cost) = 0.90$		$k(Weight) = 0.85$		$k(S.Life) = 0.85$		-0.998
Cost ($)	$U(Cost)$	Weight (grams)	$U(Weight)$	S. Life (Al=1.0)	$U(S.Life)$	
2	1	300	1	0.9	0	
4	0.98	350	0.98	1.1	0.7	
6	0.90	400	0.80	1.2	0.75	
10	0.82	450	0.65	1.5	0.85	
22	0.20	480	0.20	2.0	1	
25	0	500	0			

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