QFD to Direct Value Engineering in the Design of a Brake System

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Abstract

Value Engineering is a powerful methodology to reduce the cost of mechanical systems by looking for a mismatch between the function of a component and the cost of the component. Hayes Brake, in the design of a new braking system, used QFD to determine the importance of various braking functions and performance levels to users, and then subsequently design both a lower-cost alternative as well as a high performance model. This paper will describe the customer evaluation process including a web-based questionnaire, the deployment through the House of Quality to a Function Analysis, multiple cost modeling studies, and the design concepts that were created and proposed to the OEM. This product is still waiting approval from the OEM.

Key Words

Brakes, QFD, Quality Function Deployment, Value Engineering

What is QFD

Quality methodology traditionally focused on improving existing products and processes based on reported problems from the field or factory floor. Japan, in the 1960s expanded this approach in two significant directions – continuous improvement and Quality Function Deployment (QFD). Continuous improvement, even in its latest manifestation, Six Sigma, does not wait for problems to occur but in the spirit of the 5th of the late Dr. Deming's 14 Points for Transforming Management, "Improve constantly and forever every process for planning, production and service," seeks out opportunity to add value to the company and product.

QFD is an approach that directs these improvement efforts specifically to new products and services. The ideal is to design and build quality as defined by customer satisfaction and value into new products. In other words, to get it right the first time. Further, QFD looks to improve the new product development (NPD) process itself by reengineering the cross-functional contributions of each department to assure they meet certain standards of timeliness, content, and quality. These two aspects of Comprehensive QFD are shown in the original concept model developed by Dr. Yoji Akao, co-founder of QFD, in **Figure 1.**

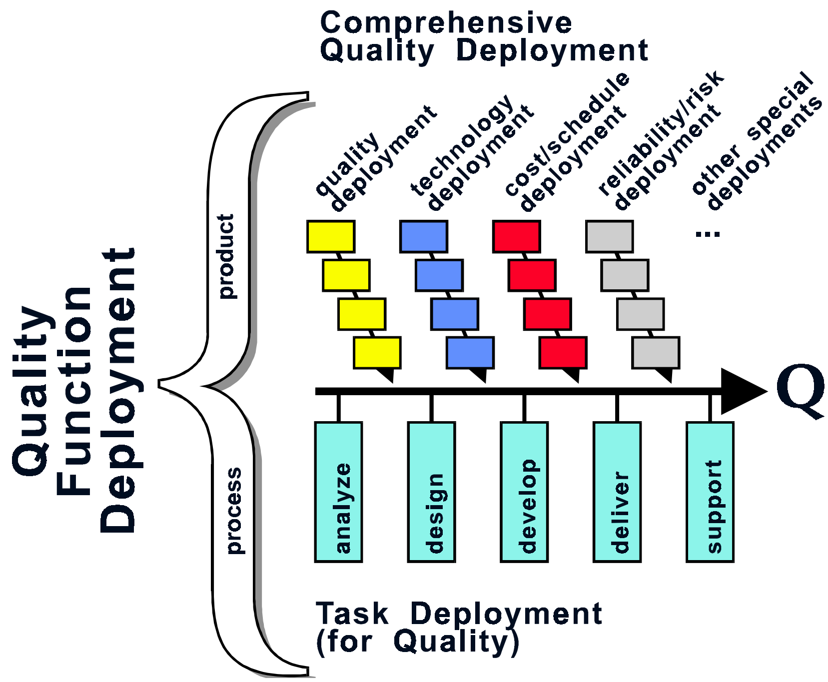


Figure 1. Comprehensive QFD Concept. [Akao 1990]

In this paper we will focus on the top portion of figure 1, Comprehensive Quality Deployment, and our study will look at various deployments such as quality deployment, function deployment, technology deployment, and reliability deployment. For cost deployment we went further and employed Value Engineering principles to reduce costs of the new brake system.

What is Value Engineering

Value Analysis was developed by Larry Miles of General Electric during World War II to lower the cost of manufactured products. Miles' approach was to examine the function of the product rather than the product itself, so that designers could develop alternative solutions to perform the same functions at a lower cost. Through its methods of Value Analysis and Function Analysis, value mismatches are identified where the criticality of the function and the cost of the parts that perform that function are examined. Where cost exceeds the value of the function, cheaper alternatives to those parts are sought.

The Godzilla Project

Hayes Brake, LLC began in 1946 as a manufacturer of caliper disc brakes. Hayes is a specialist in the disc brake applications for recreational, construction, agricultural and military vehicles, motorcycles, bicycles, as well as other types of mobile and stationary equipment. Among its over 300 Original Equipment Manufacturer customers (OEM) are such well-known brands as Polaris, John Deere, JCB, Caterpillar, Textron, Ariens, E-Z Go, Tennant, Volvo, Trek, Schwinn, and Giant. In 1999, we obtained ISO 9001 certification, further demonstrating our commitment to quality and continuous improvement.

This commitment to quality followed its natural course to applying it to future products, and QFD was attempted in order to capture the "voice" of the customer and to build that into the new design. The Godzilla project is planned for 2006 market delivery as a new brake system for a motor vehicle OEM. Since we were only slightly familiar with QFD, we decided to tap the expertise of Glenn Mazur, who introduced us to the Comprehensive QFD model developed by the co-founder of the QFD method, Dr. Akao. Unlike the simpler 4-Phase QFD models followed by parts supplier restricted to build-to-print designs, the Comprehensive QFD model is optimized for the kind of "outside-the-box" system level design we were considering. Little did we appreciate at the start that Comprehensive QFD would allow us to evaluate the functional, performance, reliability, and cost parameters of our product.

Mazur helped us customize the Comprehensive QFD model to the unique considerations of the Godzilla project. This paper will show some of the key steps as well as excerpts of some of the analyses and charts. For confidential reasons, we cannot reveal much about the OEM, their needs, or details of the study. We hope, however, that readers can get a feel for the power of QFD, the need to fit QFD to the project, and the focus and clarity that QFD can bring to a new product development team.

The Customized QFD Process

Figure 1 shows many of the deployments of QFD, but they are not all used on every project. The ability to select the appropriate tools and their sequence comes only with extensive study and many applications. Failure to customize can result in poor compliance by the product development team, wasted time and efforts, product delivery or launch delay, and suboptimal design. It is because the risks are so high that the QFD Institute began in 2000 a QFD certificate program to help standardize the QFD training process. Hayes Brake was one of the first in North America and in the automotive sector to earn both the QFD Green Belt® and QFD Black Belt® certificates for its team members. The sequence portrayed by the following sections excludes certain steps deemed confidential by Hayes Brake, and while presented serially, actually included parallel activities.

The QFD Team

Beginning in April 2001, we began by training 22 engineers from across the company as QFD Green Belts®. The group included sales engineers, R&D engineers, and quality engineers from all our product sectors. From this group, nine were selected for QFD Black Belt® training in July to focus on the Godzilla project. Of these, four went on to earn the QFD Black Belt® certificate. These were Jim Dimsey, Tim Abhold, Dan Haas, and Antonio Rodriguez.

Business and Project Goals

Since out project timeline was five years in length, it was crucial we understand the long-term expectations that Hayes Management had for the Godzilla project. These goals were elucidated by the QFD team members in conjunction with management, and were organized using the standard Management and Planning tools [Mizuno 1988, Brassard 1989] used in QFD, namely the Affinity Diagram and Hierarchy Diagram. Finally, they were prioritized using the Analytic Hierarchy Process (AHP). [Saaty 1990] Among the goals were the following; number 2 carried the highest priority.

1. Financial goals such as contribution to margin, internal rate of return (IRR) and net present value (NPV).
2. Position as the supplier of choice with this OEM for technical competency, meeting or exceeding requirements for quality, cost, and delivery, and being able to demonstrate and follow a product development roadmap.
3. Develop new products for new customers.
4. Create a superior new product development process the rest of the company could emulate.

Key Customers

It is important to capture the "voice" of those customers that can directly and indirectly lead to project success. As a component supplier, the QFD forced us to look not only at the OEM engineers (our traditional concept of who the customer is), but also at the end consumer who uses our installed brake system and the dealer mechanic who must maintain the performance and function of the brake system. In terms of the consumer, we also had to consider what driving conditions provided the biggest challenge to brake function and performance. These were laid out in a Customer Segments Table shown in **Table 1**.

Table 1. Customer Segements Table (partial)

Customer Segments							
Who	**What**	**When**	**Weather**	**Surface**	**Where**	**Why**	**How**
Customer	Delivery	Spring	Rain	Asphalt	Europe	Fun	Hardcore
Eng	Commute	Summer	Dry	Concrete	Asia	Image	Extreme
Purchasing	Leisure	Fall	Dusty	Gravel	US/Canada	Transport	Trailers
Marketing	Status	Winter	Hot	Sand	Latin America	OTJ	Side Cars
Service	Patrol	Day	Humid	Mud	Aust/NZ	In lieu of car	w/Passenger
End User							
White Male, 35-49							
Women 65th%							

For the OEM customer, we were interested in spending the most time with those who would most influence the decision to use our system and could spend time with us at this early stage. To get our team members to reach agreement on which OEM customer would be most influential, we first examined how the OEM made their decisions and who were the key drivers of the process. We used the Relations Diagram of the Management and Planning Tools to diagram this process (**Figure 2**.) and the AHP to further narrow our OEM interface to platform engineering and chassis engineering. Negotiating their requirements is still in process.

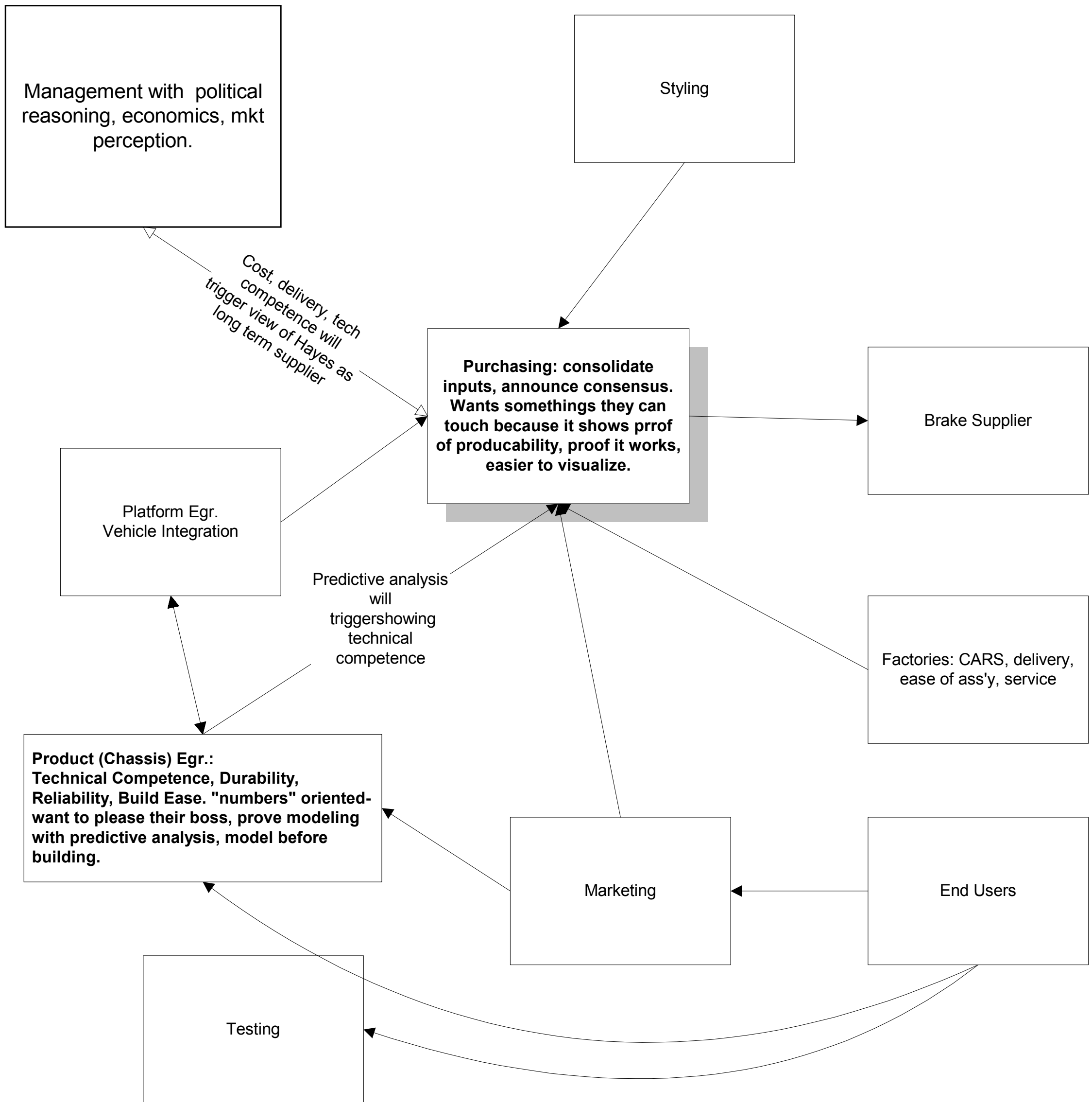


Figure 2. OEM Supplier Decision Process

Prioritization of key end users followed a different process that led us to road rallies and to professional drivers, among others. We will show some of the results of the end user studies in the following sections of this paper.

Voice of the Customer

In consumer behavior, there have been several studies [Kano 1984, Nonaka 1995] that purport that spoken words are not necessarily a complete or accurate portrayal of all issues or concerns. In QFD, extensive voice of customer analysis is done through a series of tools that attempt to discover, uncover, structure, and then prioritize these into a set of customer needs or Demanded Quality. These tools include the Management and Planning tools, the AHP, as well as specialty voice of customer tables [Mazur 1997]. The Voice of Customer Table -1 (**Table 2.**) takes the verbatims of the customer in the context of actual or possible scenarios of use and rewords them into additional unspoken data. This analysis helps the team expand their understanding of customer needs beyond the obvious into areas where hidden needs may emerge in the future. In the excerpt here, we see that the spoken concern about a "soft lever" may indicate other concerns for shorter stops, quicker stops, etc. To develop differentiated products, going beyond the stated needs has proven to be useful.

Table 2. Voice of Customer Table -1 (partial).

	This is used to record current demanded quality items and to brainstorm new demanded quality items, applications, and uses. It is used to widen design assumptions. The data comes from customer interviews. This data goes into VOCT-2.														Step #3
			Use												
Customer	Voice of Customer	Customer Char.	Who		What		When		Where		Why		How		Reworded Data
			I/E	Data	I/E	Data	I/E	Data	I/E	Data	I/E	Data	I/E	Data	
	Soft lever.		E		E	slowing	I	parade	E		E	obey law	I	front only	Deceleration/lever displacement has too low slope. Shorter stops. Stops quickly. No air in system. Doesn't fade. Stops well at any altitude.
			E	general	E	stopping	E	patrol	I	all weather			I	rear only	Less lever travel before I stop.
			E	himself	E	speed control	E	Gen'l transportation	E	MKE	E	avoid collision	I	combined	Too much dead stroke.
							E								Won't pinch fingers
					E	vehicle control	E	recreation							Perception of less control

These reworded data were then grouped into product-independent demanded quality items and product features such as performance, function, solutions, etc. using the Voice of Customer Table – 2 (**Table 3**), affinity diagram (**Table 4**), and hierarchy tree (**Table 5**). Complaints such as "soft lever" are reworded into positive needs such as "firm lever." The hierarchy was used to create a web-based survey for users to prioritize their needs and to compare competing brake systems, since it was difficult to get customers to isolate brake performance from other components and systems.

Table 3. VOCT-2 (partial)

This is used to sort reworded data into appropriate columns for later matrix deployment. The data comes from VOCT-1 and v							
VOCT-2							
Customer Benefits	Product Features						
Cust Needs/Demanded Quality	Qual Char (QC)	Function	Failure	Reliability	Technology	Parts/Part Char.	Pr
Increase time between pad changes	Life of F/M (HP x hr)/in^3			Pad life		pad geometry	form
Increase time between pad changes	Inches		Tapered Pad wear			caliper geometry, Pad geometry	
Engages quickly.	Lever displacement (inches)	Lever movement to engage pads					
Confortable stop					Expected Option	Adjustable lever	

Table 4. Demanded Quality Affinity Diagram (partial).

This is used to initially organize Demanded Quality items into groups. The information comes from VOCT-2 and will be organized further in the Demanded Quality Hierarchy Tree.			
Brakes Well	**Comfortable braking**	**Environmentally Friendly**	**Looks Good**
Confident braking under all conditions	Quiet braking	Easy to recycle materials	Styling compliments bike performance
Consistent braking for life of pads	Quiet when not braking	Environmentally-safe materials	Colors compliment bike colors
Easy to control amount of brake power	No fatigue from braking	Recyclable component materials	Easy to keep up appearance
	Brake controls are easy to use	Environmentally safe fluid	High performance look
Engages quickly	Firm lever	Environmentally safe coatings	Caliper smaller

Table 5. Demanded Quality Hierarchy (partial).

This is used to establish a hierarchy of demanded quality items and to identify missing ones. The data comes from the affinity diagram. This data will then go into the questionnaire and rows of the HoQ.			
Comfortable braking	Quiet braking	No squeel/moan	
		No rattling	
	Quiet when not braking	No free running pad drag	
		No rattles	
	No fatigue from braking		
		Foot fatigue	
	Brake controls are easy to use		
		Non-slip lever	
		Easy to locate	
		Easy to use	
		Accommodating Small people	More sales to woman
		Foot comfortable	Lever feels good
	Firm lever		

Quality Characteristics

Demanded Quality statements represent product-independent customer needs and can be fuzzy and qualitative. In QFD, they must be converted into measurable design elements that can then substitute as target specifications. These are called Quality Characteristics and can be extracted directly from each Demanded Quality item, as shown in **Table 6**. It is recommended that Quality Characteristics be organized with the affinity diagram and hierarchy, as shown in **Table 7** and **Table 8**.

Table 6. Quality Characteristics Table (partial).

This converts imprecise customer demands into quantitative/measurable characteristics. This table takes data from VOCT-2 . This data will feed into the Quality Characteristics Affinity & Hierarchy Diagrams, and HoQ.			
Demanded Quality	**Quality Characteristic**	**Measurement**	**Demanded**
Firm lever	Fluid compressibility	Modulus	
	System efficiency	%	
	Fluid volume	in^3	
	pressure vs dia. of brake line	psi vs inches	
	caliper stiffness (pressure vs deflection)	psi vs inches	
	Lever stiffness (force vs deflection)	lbsf vs inches	

Table 7. Quality Characteristics Affinity Diagram (partial).

This orginizes Quality characteristics into natural groups.
Data comes from Quality characteristic table. Data from

			Pl
Fluid	**Lever**	**Pedal**	
Degas altitude of fluid	Lever ratio	Pedal ratio	
Air absorption of fluid	lever width		
Boiling point of fluid	Grip size		Disc
Fluid compressibility	Lever finish		Pa
			Ro
			Dis
			Perf
Fluid	**Lever**	**Pedal**	
Volume of Fluid Behind Piston	Lever force vs. travel	Pedal force vs travel	F
Heat Trans. To Fluid	Lever dead stroke	Pedal dead stroke	#
	Lever stiffness (force vs deflection)		
	Lever Stroke vs Max. decel		

Table 8. Quality Characteristics Hierarchy (partial).

This orginizes data from the Quality Characteristic Affinity Diagram into a tree to help indentify missing Characteristics. This data will go into the HoQ.

ysical Characteristics	Fluid	Degas altitude of fluid
		Air absorption of fluid
		Boiling point of fluid
		Fluid compressibility
	Lever	Lever ratio
		lever width
		Lever finish
		Grip size
	Pedal	Pedal ratio
		Rotor Mass
		Disc thickness variation (rr)

mance Characteristics	Fluid	Volume of Fluid Behind Piston
		Heat Trans. To Fluid
	Lever	Lever force vs. travel
		Lever Stroke vs Max. decel
		Lever dead stroke
		Lever stiffness (force vs deflection)
	Pedal	Pedal dead stroke
		Pedal force vs travel
	Switch	Force to operate switch
		# of operations of switch
		Air Flow

House of Quality

Central to the QFD process is the conversion of the voice of the customer as represented by Demanded Quality into the voice of the engineer as represented by the Quality Characteristics. This is handled through a special matrix dubbed the House of Quality, **Table 9.**, because of its several rooms, which will be explained below.

1. **Demanded Quality.** As explained above, these are qualitative, product-independent expressions of customers needs and wants, as learned from customer visits, reworded in the VOCT-1, categorized in the VOCT-2, and then grouped and structured with the affinity diagram and hierarchy.
2. **Importance.** Based on the responses to the web survey, the relative importance of each Demanded Quality is established, with the purpose of directing improvement activities in those areas that matter most to the customer.

3. **Preferred Competitors.** To further focus improvement activities, the web survey will ask customers which of the competing models best satisfy their needs. Since brake components are often difficult for customers to single out in their evaluation, we asked about specific vehicles for which we new the competing brake suppliers.
4. **Business and Marketing Strategy.** The new brake system is positioned to meet or exceed the competition for the important Demanded Quality where there is a preferred competitor. Sales strategy was also incorporated into this positioning.
5. **Quality Characteristics.** The Quality Characteristics hierarchy developed above is juxtaposed with the Demanded Quality.
6. **Relationships.** The strength of the relationships between each Quality Characteristic and Demanded Quality is determined by the QFD team. A numeric scale is applied, with a strong relationship at 9, medium at 3, and weak at 1.
7. **Multiple Relationships Summed.** The Importance, Preferred Competitors, and Business and Marketing Strategy are quantified and amalgamated into a single number called the Demanded Quality Weight. This Weight is then multiplied by the Relationship scale weight, and the resulting products are summed column by column. This has the effect of converting the Demanded Quality Weights into Quality Characteristic Weights, thereby directing improvement activities in specific design and engineering terms.
8. **Target Specifications.** A competitive tear down can be made for each high priority Quality Characteristic, and target specifications can be set to meet or beat the preferred competitor.

Thus, the House of Quality is used to convert the prioritized voice of the customer into the prioritized voice of the engineer.

Function Deployment

Key to establishing the value engineering studies is the function analysis, as stated above. This process requires determining the ratio between the functional contribution and the cost of that function as determined by its systems and parts. To establish the functional contribution in a new product design, QFD looks at the relationships between demanded quality and function.

The first step is to build a function tree that uses its nodes and leaves to explain the whys and hows of each function. In **Table 10,** as you move to the right, each set of leaves explains *how* the node to the left is performed; as you move to the left, each node explains *why* the leaves to the right are performed.

The values of each function are then calculated by placing the function tree in juxtaposition in a matrix, with the demanded quality hierarchy and/or with the quality characteristic hierarchy. Since we have already calculated demanded quality weights and quality characteristic weights in the House of Quality, these weights can be translated into function weights using the same matrix math used in the House of Quality. **Tables 11 and 12**

Table 9. House of Quality.

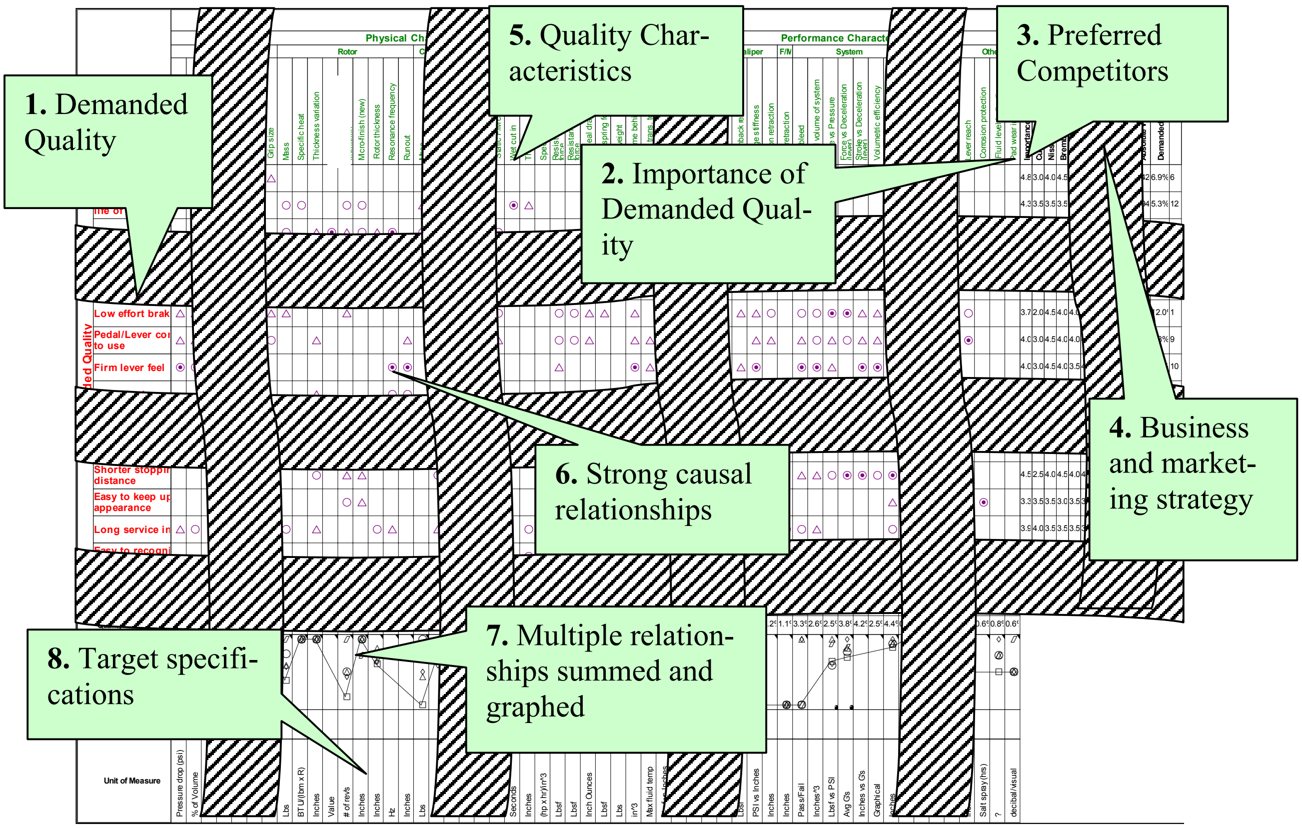
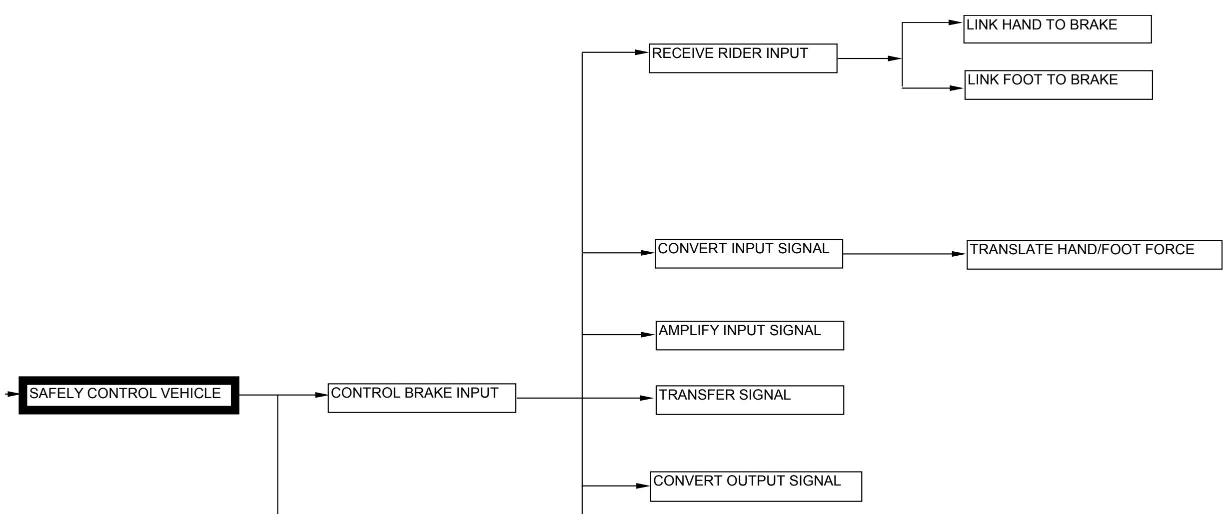


Table 10. Function Tree (partial).



are extracts from these matrices.

Table 11. Demanded Quality-Function Matrix (partial).

DQ/Funct. Thread		Function: Recieve Rider Input	Convert Input Signal	Amplify Input Signal	Transfer Input Signal	Convert output Signal	Feedback Signal	Convert Kenetic Energy	Control Wheel Lockup	Demanded Quality Weight
Demanded Quality	Easy to control amount of brake power	○	⦿	⦿	○	⦿	⦿	⦿	⦿	8.3
Demanded Quality	Low effort braking	⦿	⦿	⦿	○	○	⦿	⦿		12.2
Demanded Quality	Pedal/Lever comfortabl to use	⦿		○						5.8
Demanded Quality	Firm lever feel	○	○	⦿	○	○	⦿			5.8
Demanded Quality	Quick brake engageme	○	⦿		○	⦿			○	8.9
Absolute Weight		287	353	325	202	336	309	388	303	
Function Weight		7.0%	8.0%	8.0%	5.0%	8.0%	7.0%	9.0%	7.0%	

Table 12. Quality Characteristic-Function Matrix (partial).

QC/Funct. Thread				Functions: Recieve Rider Input	Convert Input Signal	Amplify Input Signal	Transfer Input Signal	Convert output Signal	Feedback Signal	Convert Kenetic Energy	Control Wheel Lockup	Control Component Position	Compliment Vehicle Styling	QC Weight
Quality Characteristic	Physical	Lever	Ratio		⦿	⦿			○		⦿		△	4.0%
Quality Characteristic	Physical	Lever	Width	⦿	△	△							⦿	2.2%
Quality Characteristic	Physical	Lever	Grip size	⦿		△							⦿	0.8%
Quality Characteristic	Physical	Other	Return spring force (lever)		△	△			△		△	⦿		1.2%
Quality Characteristic	Performance Characteristic	Lever	Lever force vs Travel			○	⦿		⦿	○	⦿			2.7%
Quality Characteristic	Performance Characteristic	Lever	Lever dead stroke			○	○				△			1.6%
Quality Characteristic	Performance Characteristic	System	Force vs Pressure				⦿	⦿	⦿	○	⦿			2.5%
Quality Characteristic	Performance Characteristic	System	Force vs Deceleration (lever)				⦿	⦿	⦿	⦿	⦿			3.9%
Quality Characteristic	Performance Characteristic	System	Stroke vs Deceleration (leve			○	⦿	⦿	△		○			4.2%
Quality Characteristic	Performance Characteristic	Other	Lever reach	⦿	△	○			△		○			2.8%
Absolute Weight				0.52	0.42	2.37	2.66	3.02	2.56	1.83	4.11	0.87	0.87	
Function Weight				2.0%	2.0%	9.0%	11.0%	12.0%	10.0%	7.0%	16.0%	3.0%	3.0%	

Reliability Deployment

The redesign a product enables an opportunity to design out past and potential failures. It is not uncommon for the QFD team to prioritize reliability and safety studies based on the threat they pose to customer satisfaction as expressed by the Demanded Quality. First, failure modes are extracted from warranty and safety records, field complaints and reports, and other sources. These can be structured into a hierarchy, known as a fault tree (**Table 13**), and then juxtaposed into matrices with Demanded Quality (**Table 14**), Quality Characteristics (**Table 15**), and Functions (**Table 16**) to show failure to satisfy, failure to perform, and failure to function, respectively. High priority failures are then candidates for reliability engineering studies.

Table 13. Fault Tree (partial).

Vehicle doesn't stop	Braking efforts to high
	No brake pressure
	Air in fluid
	Brake fades
	Brake leaks
	[illegible]

Table 14. Demanded Quality-Reliability Matrix (partial).

DQ/Reliability Thread		Reliability								
		Braking efforts to high	No brake pressure	Air in fluid	Brake fades	Excessive lever travel	Brake sticks	Lever/pedal pusles	Tire is easiliy locked	**Demanded Quality Weight**
Demanded Quality	Easy to control amount of brake power	⦿	⦿	○	○	○	⦿	○	⦿	4.4
	Low effort braking	⦿	⦿	⦿	○	○		△	⦿	3.7
	Pedal/Lever comfortabl to use	○						△	△	4.0
	Firm lever feel	○	⦿	⦿	⦿	○		○	○	4.0
	Quick brake engageme		⦿			⦿	⦿		○	4.1
Absolute Weight		**221**	**270**	**254**	**196**	**92**	**224**	**122**	**199**	
Failure Weight		11%	14%	13%	10%	5%	12%	6%	10%	

Table 15. Quality Characteristic-Reliability Matrix (partial).

QC/Reliab. Thread				Reliability: C	Braking efforts to high	No brake pressure	Air in fluid	Brake fades	Excesive lever travel	Brake sticks	Lever/pedal pusles	Tire is easiliy locked	QC Weight
Quality Characteristic	Physical	Lever	Ratio	△	⦿				○		⦿	⦿	4.0%
			Width		△								2.2%
			Grip size										0.8%
		Other	Return spring force (lever)	⦿	△					⦿		△	1.2%
	Performance Characteristic	Lever	Lever force vs Travel		△	⦿	⦿	⦿	⦿			○	2.7%
			Lever dead stroke		△	⦿	⦿		⦿			○	1.6%
		System	Force vs Pressure		⦿	⦿	⦿	⦿			⦿	⦿	2.5%
			Force vs Deceleration (lever)		⦿	⦿	⦿	⦿			⦿	⦿	3.9%
			Stroke vs Deceleration (leve		△	⦿	⦿	○	⦿			△	4.2%
		Other	Lever reach		△							△	2.8%
Absolute Weight				0.25	3.03	2.94	3.36	2.46	2.33	0.62	1.51	3.17	
Failure Weight				1%	12%	12%	14%	10%	9%	3%	6%	13%	

Table 16. Function-Reliability Matrix (partial).

Function/Reliability Matrix		Reliability: Braking efforts to high	No brake pressure	Air in fluid	Brake fades	Excesive lever travel	Lever/pedal pulses	Tire is easiliy locked	Function Weight
Function	Recieve Rider Input	⦿	⦿		○	⦿	○	⦿	7%
	Convert Input Signal	⦿	⦿		○	△		⦿	8%
	Amplify Input Signal	⦿	⦿	○	○	△		⦿	8%
	Transfer Input Signal	○	⦿	⦿	○	△		⦿	5%
	Convert output Signal	⦿	⦿	○	○	△		⦿	8%
	Feedback Signal	○	⦿	○	○	△	⦿	⦿	7%
Absolute weight		4.80	7.71	2.41	3.95	4.25	2.40	5.86	
Reliability Weight		11%	17%	5%	9%	10%	5%	13%	

Technology Deployment

Having analyzed high priority Quality Characteristics to set target performance specifications, Functions to drive value engineering, and Failure Modes to enable reliability and safety studies, it is prudent to identify where technology competencies as well as gaps lie. These can be done by first identifying our core technologies and then examining whether they are sufficient or not to meet the performance, function, and reliability requirements established above. **Table 17** is an example of checking technology competencies against functional requirements.

Table 17. Function-Technology Matrix (partial).

Function/Technology (capability)		Technology (capability)					
		Brake By Wire (BBW)	**Fast Fill Mc**	**High Runout Complient**	Rim Braking	**Variable Reach Input**	**Pad Retraction**
Function	Recieve Rider Input	○	⦿		⦿	⦿	
	Convert Input Signal	○	⦿		⦿	⦿	
	Amplify Input Signal	○	⦿		⦿	⦿	
	Transfer Input Signal	○	⦿		⦿		
	Convert output Signal	○		⦿	⦿		
	Feedback Signal	△			△		
	Transfer torque	⦿		⦿	⦿		⦿
	Transfer Heat	⦿		⦿	⦿		⦿
	Control Wheel Lockup	△					
Use:			Y	Y		Y	Y

New Concept Selection

Based on the technology gaps identified above, new design concepts were proposed to solve these problems. These new concepts were then prioritized using the Pugh Concept Selection Matrix (**Table 18**).

Table 18. Concept Selection Matrix (partial).

QC/Concept Matrix			Concept								
			Fluid					Fast F			
			BOC DOT 4	DOT 3	DOT 5	*Mineral Oil*	S	BOC Single piston/bore	Side by Side Pistons	Two pistons in line	Two circuits
Physical Characteristic	Fluid	Degas altitude		⊗	−	+	+				
		Air absorption		⊗	−	+	+				
		Boiling point		−	+	−	−				
		Compressibility		⊗	−	+	+				
	Lever	Ratio							+	+	+
		Width									
		Grip size									
	er	Mass									

Parts Deployment

From the selected concepts, an analysis of the required parts for the master cylinder and caliper assemblies was made. This was used to establish part priorities for later comparison with function priorities in the value engineering study. First, a Parts Function Tree (**Table 19**) was created to identify all required functions at the component level. This differs from the prior function tree which was done at the system level. Part priorities are calculated from the Quality Characteristics priorities using the relationships matrix, as before. **Table 20** shows the front master cylinder parts matrix. A Parts/Function relationship is established by adding across the row. Each column is then normalized to get part percentage relationship to functions, shown in **Table 21**.

Table 19. Master Cylinder Component Function Tree (partial).

Locate components	Hold parts	Hold fluid
		Hold pressure
	Affix parts	Attaches body on Vehicle
		Attaches resevoir cover
		Attaches resevoir gasket
		Attaches clamp

Table 20. Quality Characteristics-Front Master Cylinder Parts Matrix (partial).

Quality Characteristic			Quality Characteristic/Front MC Parts	Mc Body	Clamp	Clamp Screws	Lever	Pivot Pin	Bushing (lever pin)	Retaining Ring (lever)	Sight Glass	Cover Gasket	P
Quality Characteristic	Physical	Lever	Ratio				⦿						
			Width				⦿						
		Other	Resistance lever apply force				⦿	△	○				
			MC weight	⦿	○	△	⦿	△	△	△	△	△	
	Performance	Lever	Lever force vs Travel	⦿			⦿						
			Lever dead stroke	⦿			△						
		System	Force vs Pressure	⦿			⦿						
			Stroke vs Deceleration (leve	⦿			⦿						
		Oth	Lever reach	⦿			⦿						
			Absolute Weight	2.60	0.10	0.10	3.50	0.10	0.01	0.01	0.10	0.30	0.1
			Part Weight	23.90	0.52	0.50	31.74	0.61	0.34	0.01	0.50	2.59	0.

Table 21. Front Master Cylinder Parts-Function Matrix (partial).

Part/Function Matrix	Hold fluid	Hold pressure	Attach body to vehicle	Attach resovoir cover	Attach resevoir gasket	Attach clamp	Hold hydraulic line	Position mirror	Position turn signal	Position spring	Position lever	Position port timing	Position wiper	Flow uni-directional	Create pressure	Feedback output	Input for hand	Flow fluid bi-directional	Vent air	Push piston	Amplify input
	Functions																				
Mc Body	⦿	⦿	⦿	⦿	⦿	⦿	⦿	⦿	⦿		⦿	⦿	⦿		⦿	⦿		⦿			
Clamp			⦿													⦿					
Clamp Screws			⦿			⦿										⦿					
Lever											⦿	⦿			⦿	⦿	⦿			⦿	⦿
Pivot Pin											⦿	△			○	⦿				○	
Bushing (lever pin)												△			△	△				△	
Retaining Ring (lever)																					
Sight Glass		△																			

Value Analysis/Value Engineering

Cost is always an important factor in product development. Part cost is generally left out of the HoQ and other matrices due to its ability to skew/overshadow the importance of other characteristics. Value analysis and value engineering allow you look at cost from an end users perspective or from an engineering point of view. This should help identify potential part reductions and possibly combine part functions to keep cost in line with value.

Value Analysis

The theory behind value analysis is to put cost into the areas that have the most value to the customer. The value analysis takes the parts percentage cost based on the total system part cost and ratios it against value of the part from the Quality Characteristic/Part Matrix. This was first done for an existing system. This information can be put it in a couple of different forms. In a bar graph form (**Figure 3**) you would divide percent part cost by percent part importance from matrix. A value of (1) would be a part with equal cost and customer value. The warning label is a good example (66.06) of high cost vs low customer value. In this same chart, the opposite is true for the lever. The lever shows (.88) low cost vs high value. The data could also be plotted value vs cost with a line drawn at slope of 1. The idea here would be to drive the data points toward the slope **(Figure 7).**

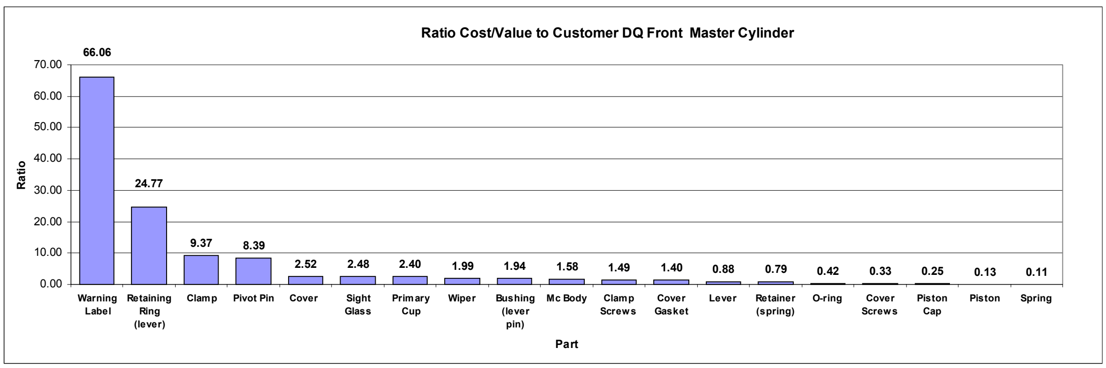


Figure 3. Value Analysis Ratio of Current Master Cylinder Parts Cost to Value of Customer Demanded Quality (partial).

This same value analysis was done on a proposed Fit & Function (FF) system (**Figure 4**) and a proposed QFD (**Figure 5**). Overall results comparing all three charts, the current system had (4) parts with a ratio over (7), the new FF system had only (1) and the QFD system had only (2). Keep in mind as parts are eliminated or cost reduced, other parts ratios can be driven up. Further improvements could be made to this system given a relaxation of customer requirements. For instance incorporating the clamp into the body drives all components close to the 1:1 ratio, almost an optimal system (**Figure 6**).

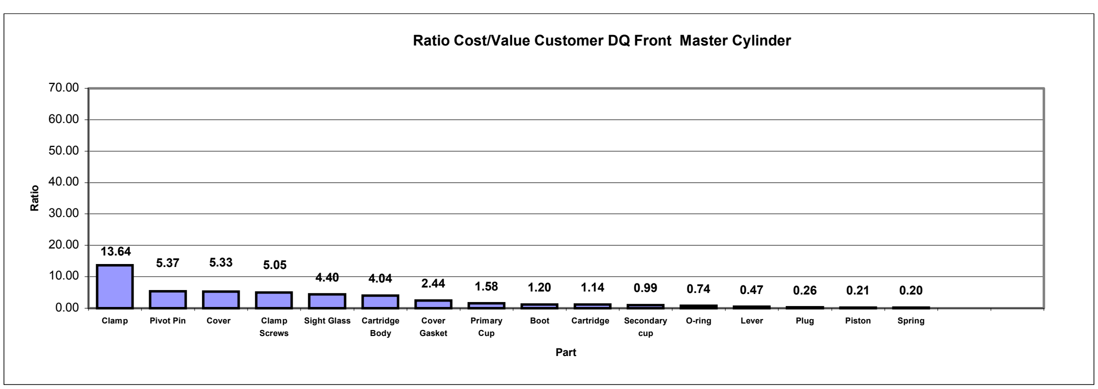


Figure 4. Value Analysis Ratio of Current Master Cylinder Parts Cost to Value of Customer Demanded Quality (partial).

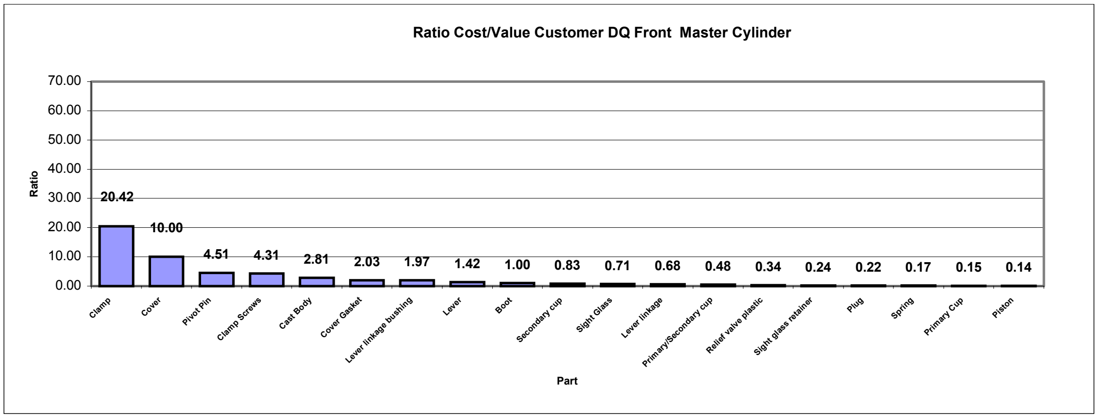


Figure 5. Value Analysis Ratio of Proposed QFD Master Cylinder Parts Cost to Value of Customer Demanded Quality (partial).

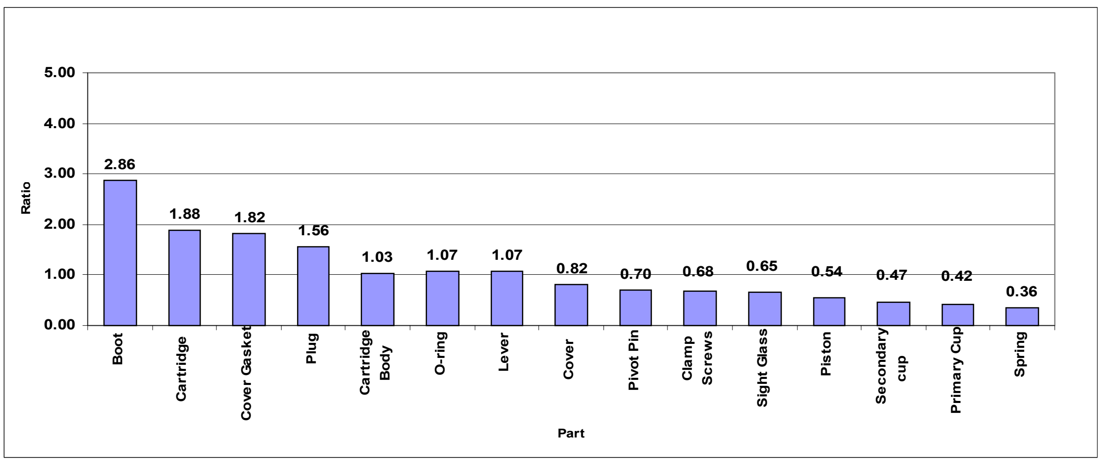


Figure 6. Value Analysis Ratio of potential Master Cylinder Parts Cost to Value of Customer Demanded Quality (partial).

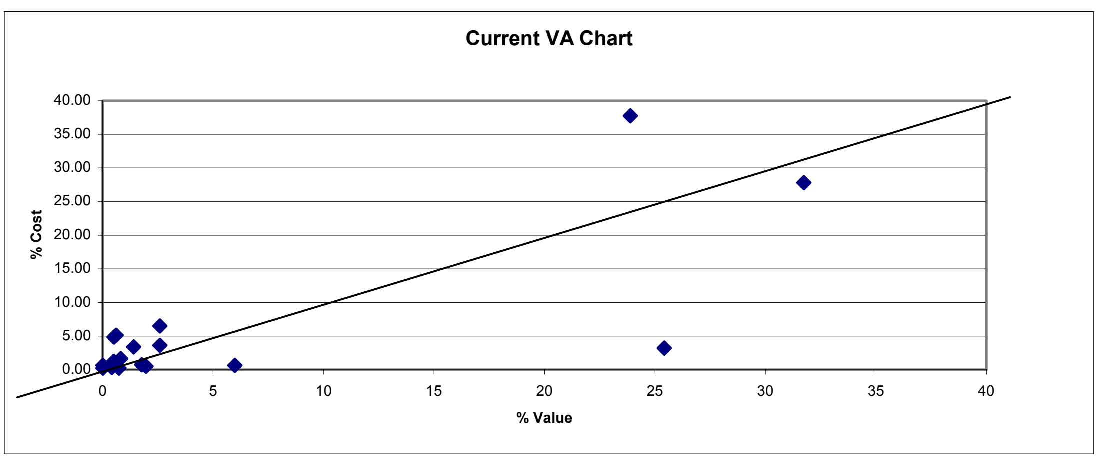


Figure 7. Value Analysis of Ratio of Current Master Cylinder Parts Cost to Value to Customer Demanded Quality (partial).

Value Engineering

This analysis should help in determining which functions might be best combined into a single part. The VE analysis takes the parts percentage cost based on the total system part cost as a ratio of the parts percent function in the system. This was first done for an existing system. This information can also be put it in a couple of different forms. In a bar graph form (**Figure 8**) you would divide percent part cost by percent part function from matrix. A value of (1) would be a part with equal cost/function percentage.

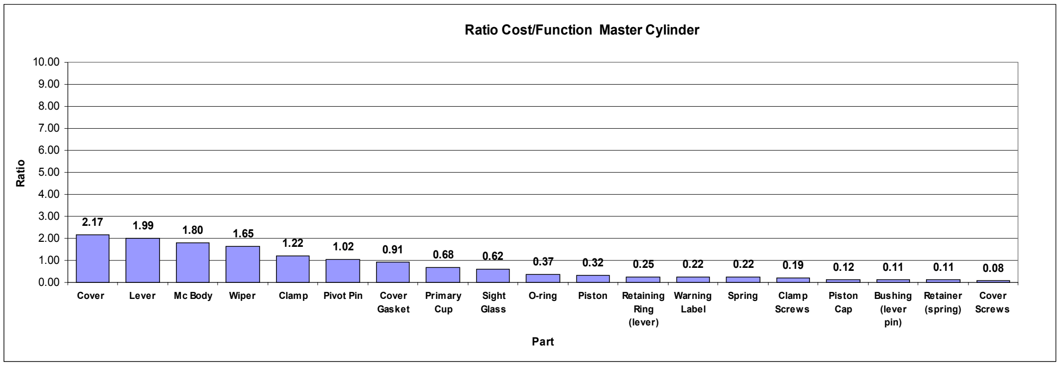


Figure 8. Value Engineering of Current Master Cylinder Cost/Function Ratio (partial).

This same value analysis was done on a proposed Fit & Function (FF) system (**Figure 9**) and a Proposed QFD (**Figure 10**). Comparing the current and FF system VE charts, you can see the FF system has driven more parts toward the 1:1 ratio. The QFD system has driven more parts toward the 1:1 ratio but has three parts over a ratio of (2) compared to the current system having only (1). These three parts should be looked at further for possible added function or cost reduction. Incorporating the clamp into the body would have the same effect here as it did in the VA chart.

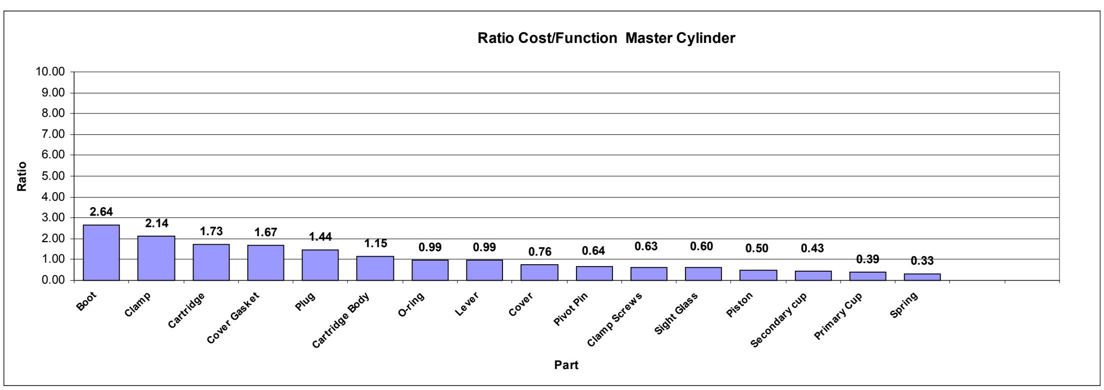


Figure 9. Value Engineering of Model FF Master Cylinder Cost/Function Ratio (partial).

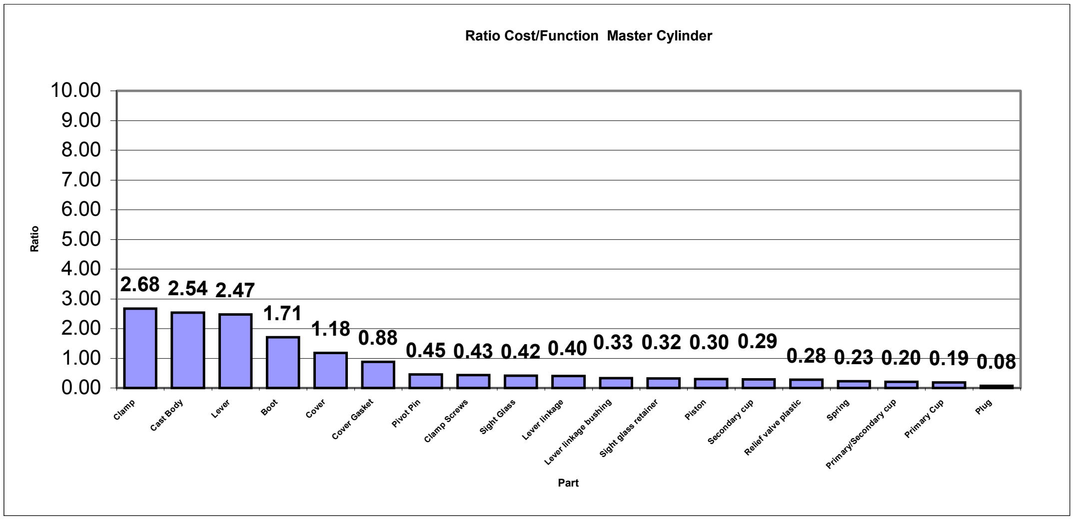


Figure 10. Value Engineering of Model QFD Master Cylinder Cost/Function Ratio (partial).

Results

From the results of the QFD work, we proposed two systems to our customer. One based solely on cost, the other on our QFD results. We believe that the extent we took in identifying the customer's needs and by quantifying any additional cost as added value, the QFD system will win out.

Conclusion

The QFD as a whole helped us to design two separate systems for a customer proposal. It gave us a tremendous increase in our knowledge-base of the competition, the end users perception of our place in the market, and a model to follow into the future so that we can be leaders in our industry.

The VA/VE portion of this proposal was something new to all of us. The idea was to show value, either from a customer point of view or an engineering perspective. The idea of adding cost is not something you strive for but given the opportunity for improvement at a cost, this should help put the cost in the most valued areas, giving the best product for the money.

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