Dynamic Benchmarking:
A Comparative Study of Automotive Suppliers

by

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Submitted to the Department of Electrical Engineering and Computer Science
and the Sloan School of Management in Partial Fulfillment of the Requirements
for the Degrees of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

and

MASTER OF SCIENCE IN MANAGEMENT

at the
Massachusetts Institute of Technology
June, 1991

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Abstract - This thesis is a comparative study of selected development practices and production practices of the Instruments & Displays unit of Delco Electronics and a major Japanese automotive supplier in the same industry segment. Both companies were examined with respect to process capability, product and process standardization, and major steps in the development process.

The analysis indicates that Delco Electronics could save over $12 million per year through improved process control and the implementation of process standards and process-driven design standards.

The thesis uses the above topics to develop the concept of design philosophy, the mechanism which guides product designs from their initial concepts to their realization in a completed design. The thesis concludes that a design philosophy which takes into account both customer needs and manufacturing capabilities can be a source of competitive advantage.

The thesis also describes a designed experiment which investigates the relationship between various design parameters and the resultant variability of air core gauges.

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Acknowledgements

I wish to thank my advisors, Steven Eppinger and John Kassakian, for their perceptive advice and constructive criticism throughout this thesis project. Their support was essential to its success.

I thank the many people at Delco Electronics whose knowledge and advice is reflected in the pages of this thesis. I particularly appreciate the support of Harry Rudolph, Dave Langdon, and Dave Ross. I also wish to thank the employees of the Japanese Supplier to which Delco Electronics was compared.

Finally, I wish to thank the Leaders for Manufacturing program for their generous support both of this thesis and of my entire graduate academic program.

Biographical Note

David Marshall, a native of St. Louis, Missouri, received a Bachelor of Arts in Computer Science and a Bachelor of Arts in Economics from Brown University in 1985. He is a member of the Rhode Island Alpha of Phi Beta Kappa and a member of Sigma Xi. Since graduating he has worked in Japan for the Japanese Ministry of Education and in the US in the St. Louis office of Andersen Consulting, Arthur Andersen & Co.

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Chapter 1: Project Overview

1.1 Introduction

This thesis is a comparative study of developmental and operational practices for automotive instrument clusters. The research was performed at the Flint, Michigan facility of Delco Electronics, and at the facilities of a Japanese supplier in the same industry, with the support of the Leaders for Manufacturing Program of the Massachusetts Institute of Technology.

Chapter 1 outlines the origins of this study, provides a summary of its results, and describes the structure of this thesis.

1.2 Origins of This Study

In the latter half of 1989, Delco Electronics contracted the development of a 1992 model year instrument cluster to a Japanese supplier (referred to hereafter as "JS"). While the primary objective of the program was to obtain business which due to resource constraints could not be engineered and manufactured internally with acceptable cost and timing, a secondary benefit was that the program afforded DE the opportunity to compare their performance against a company in the same business.

At the same time, the author and his advisors were investigating potential thesis projects at sponsoring companies of the MIT Leaders for Manufacturing Program. Since the author's primary interest was in examining development practices of a US-based and an overseas-based company in the same industry, the DE program appeared to be an ideal candidate for collaboration. At the invitation of Delco Electronics-Flint, the author joined the DE project team; this report is the result.

1.3 Lessons of Benchmarking at DE

David Kearns, CEO of Xerox Corporation, defines benchmarking as follows:

> Benchmarking is the continuous process of measuring products, services, and practices against the toughest competitors or those companies recognized as industry leaders.[1]

In other words, benchmarking involves seeking out the best practices of others in an attempt to improve one's own performance.

In his study, Camp identifies five reasons to benchmark the competition:

1. More adequately meeting end user customer requirements.
2. Establishing goals based on a concerted view of external conditions.
3. Determining true measures of productivity.
4. Attaining a competitive position.
5. Becoming aware of and searching for industry best practices.[2]

This thesis examines the practices of DE and JS from a comparative standpoint. The emphasis in this study is on identifying those operational and developmental practices used at JS which could be adapted for use at DE. To that end, this study examines practices in three areas: process capability, product/process standardization, and development processes. In comparing the performance of DE and JS in these areas, five major lessons emerge, namely:

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[1] Benchmarking: The Search for Industry Best Practices that Lead to Superior Performance, by Robert C. Camp. ASQC Quality Press: Milwaukee, WI, 1989, p. 10.
[2] Ibid., P. 27.

- the value of process capability,
- the value of product and process standardization,
- the importance of organizational learning,
- the importance of adequate development prior to hard tooling, and
- the importance of matching manufacturing capabilities with customer needs.

It should be noted that the focus of this study is on identifying practices which DE could profitably adopt from JS. While there were numerous areas in which DE practices were superior to those of JS, these were not the focus of this study. For this reason, the treatment of some DE practices may seem superficial in comparison to the attention given the comparable JS practices.

This thesis uses the above topics to develop the concept of design philosophy, the mechanism which guides engineers as they develop a design from concept to complete design. It is argued that DE and its customers could realize savings of over $12 million through the execution of a well-developed design philosophy.

In addition, this thesis describes a designed experiment performed at DE during the thesis internship. The experiment uses modified Taguchi methods to examine the relationship between various design factors and gauge accuracy for automotive gauges.

1.4 Thesis Organization

Chapter 2 outlines the organizational setting for this thesis, the Flint facility of Delco Electronics. It describes the relationship of Delco Electronics to the rest of General Motors, as well as the recent organizational history of the Flint facility. Chapter 2 also describes the basic terminology of instrument clusters.

Chapter 3 examines process capability issues at DE and JS. It then discusses the implications of different levels of process capability, and discusses mechanisms for establishing and monitoring process capability in each organization.

Chapter 4 discusses the concept of design philosophy. The chapter illustrates the concept with examples in specific aspects of the design. The relationship of design philosophy to standard DFA methodology is also discussed.

Chapter 5 discusses the role of standards in executing a design philosophy. It discusses differences in the implementation of design standards at DE and JS, as well as methods for implementing design standards. It is argued that well-chosen design standards take manufacturing processes into account, while well-chosen process standards meet the requirements of the design envelope.

Chapter 6 discusses differences in the development process at DE and JS. It examines the differences in the sequence of development steps, as well as differences in activities in similar steps. In particular, differences in the timing of hard tooling are examined, and the implications of those differences are discussed.

Chapter 7 discusses the designed experiment performed at DE. It outlines the purpose of the experiment, discusses its structure, and presents its results. The implications of these results for gauge design are discussed.

Chapter 8 summarizes the results of the thesis, and discusses their applicablity to DE. It also suggests directions for further research.

Chapter 2. Introduction

2.1 Introduction

This chapter has two purposes. First, it introduces the organizational setting at which this research was performed: the Flint unit of Delco Electronics. This unit, formerly part of the AC Spark Plug Division of General Motors, develops most Delco Electronics instrument clusters and has primary responsibility for all instrument clusters developed by Delco Electronics worldwide. Second, the chapter describes the main types of instrument clusters and the terminology associated with them.

2.2 Company Overview

Delco Electronics is a subsidiary of GM Hughes Electronics, which in turn is a subsidiary of General Motors Corporation. General Motors is one of the largest industrial corporations in the world, with sales of over $110 billion in 1989. In that year, GM sold nearly 8 million vehicles (18 percent of worldwide car and truck sales) and employed nearly 800,000 people.[1]

GM Hughes Electronics, the GM unit to which Delco Electronics belongs, accounted for $7.6 billion in sales in 1989, and employed 73,000 people. GM Hughes Electronics participates in the defense electronics, automotive electronics, and satellite communications markets.

Delco Electronics, the subsidiary with which this thesis is primarily concerned, is a subsidiary of GM Hughes Electronics. Although DE does not publish independent financial statements, its sales are estimated to be between $2 and

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[1] Source: 1989 General Motors Annual Report.

$5 billion. Delco Electronics' principal line of business is automotive electronics, which is subdivided into six segments:

> **Audio Systems.** This unit makes receivers, speakers and other audio equipment for automotive use.
>
> **Instrumentation and Air Controls(IAC).** This unit, which is subdivided into Instruments & Displays (I&D) and Air Controls, makes instrument clusters, other displays, and heater and air conditioning controls. The Flint facility at which this research was conducted is the headquarters for the IAC business unit.
>
> **Powertrain Electronics.** This group designs and makes engine controls, transmission controls, and other electronic powertrain controls.
>
> **Body Electronics.** Products made by this group include electronic key systems and airbag electronics.
>
> **Chassis Electronics.** This group makes such products as anti-lock braking systems and traction control systems.
>
> **Hybrid Electronics.** This group designs and builds integrated circuits and various sensors and components.

The Instruments and Displays portion of DE has major facilities in Flint, Michigan; Kokomo, Indiana; Liverpool, England; and Reynosa, Mexico. Sales for instruments and displays are estimated at $500 million to $1 billion annually. The I&D group makes a wide variety of instruments for both GM and non-GM customers. Major product types include:

- Mechanical Displays
- Electromechanical Displays
- Electronic Displays (i.e. fully digital displays)
- Head-Up Displays

2.3 Overview of DE-Flint

The project site for this thesis was the Flint, Michigan facility of Delco Electronics. Flint is the main engineering and manufacturing site for automotive instruments and displays. The Flint facility employs 3100 people, of whom approximately 500 are engineers. Prior to 1987, this business unit was a part of the AC Spark Plug division of General Motors. The business unit was transferred to DE in the mid-1980s when the GM Hughes Electronics subsidiary was formed. Because of the substantial electronic content of instrument clusters, and the expectation that this content would continue to rise, the Instruments & Displays unit was considered a good unit to be transferred to GMHE. (It was necessary for financial reasons related to the creation of GM class "H" stock to transfer some GM assets to GMHE when this subsidiary was first created.)

Currently, Flint manufactures displays containing mechanical, electromechanical, and electronic technologies. (Head-up displays are manufactured elsewhere.) Most DE Flint production goes to domestic GM assembly plants, although a small proportion (10-20%) goes to outside customers and GM plants outside the US.

2.4 Product Classifications

The instrument clusters discussed in this thesis can be divided into groups along five dimensions: customer, content, style or type, display technology, and speedometer technology. Each category breaks down as follows:

Customer. The major customers for DE-Flint are CPC (the Chevrolet-Pontiac-GM of Canada unit of General Motors), BOC (Buick-Oldsmobile-

Cadillac), GM Truck & Bus Division, non-domestic GM units (such as Vauxhall or Opel), and non-GM customers.

Content. Most DE customers offer vehicles with either a basic instrument cluster or a deluxe or sport version. The basic cluster (also known as a "base" cluster) may have only a speedometer, fuel gauge, and some telltales; the deluxe version (also known as a "gauge" cluster) may have as many as six gauges: speedometer, tachometer, fuel, voltage, coolant temperature, and oil pressure.

Display Technology. Instrument clusters may be either analog (i.e. using needles on a dial face) or digital (i.e. using an alpha-numeric display). In addition, the display may be viewed directly, or it may be projected or reflected from the windshield; the latter type of display is known as a Head-Up Display(HUD), and is not yet widely used. Currently, the large majority of clusters are analog, although a substantial number of digital clusters are still sold.

Style or Type. There are two major types of analog cluster: the so-called "faceplate" or unitary design, and the modular design. Faceplate designs attach all gauges to a single large dial face (the surface visible to the customer), while modular designs separate the gauges into several independent units.

Speedometer Technology. Speedometers in an analog cluster may be either mechanical (i.e. having a mechanical cable which transmits speed data to the speedometer physically in the form of rpm of the cable) or electro-mechanical (i.e. having a wire which transmits speed information to the speedometer circuit electrically in the form of electrical pulses.). Most DE speedometers today are electro-mechanical.

There are other dimensions which could be used to divide clusters into groups, such as whether the speed signal is coming from a 6-cylinder or an 8-cylinder engine, whether the speed is displayed in miles per hour or kilometers per hour, etc., but the five outlined above are generally the most significant.

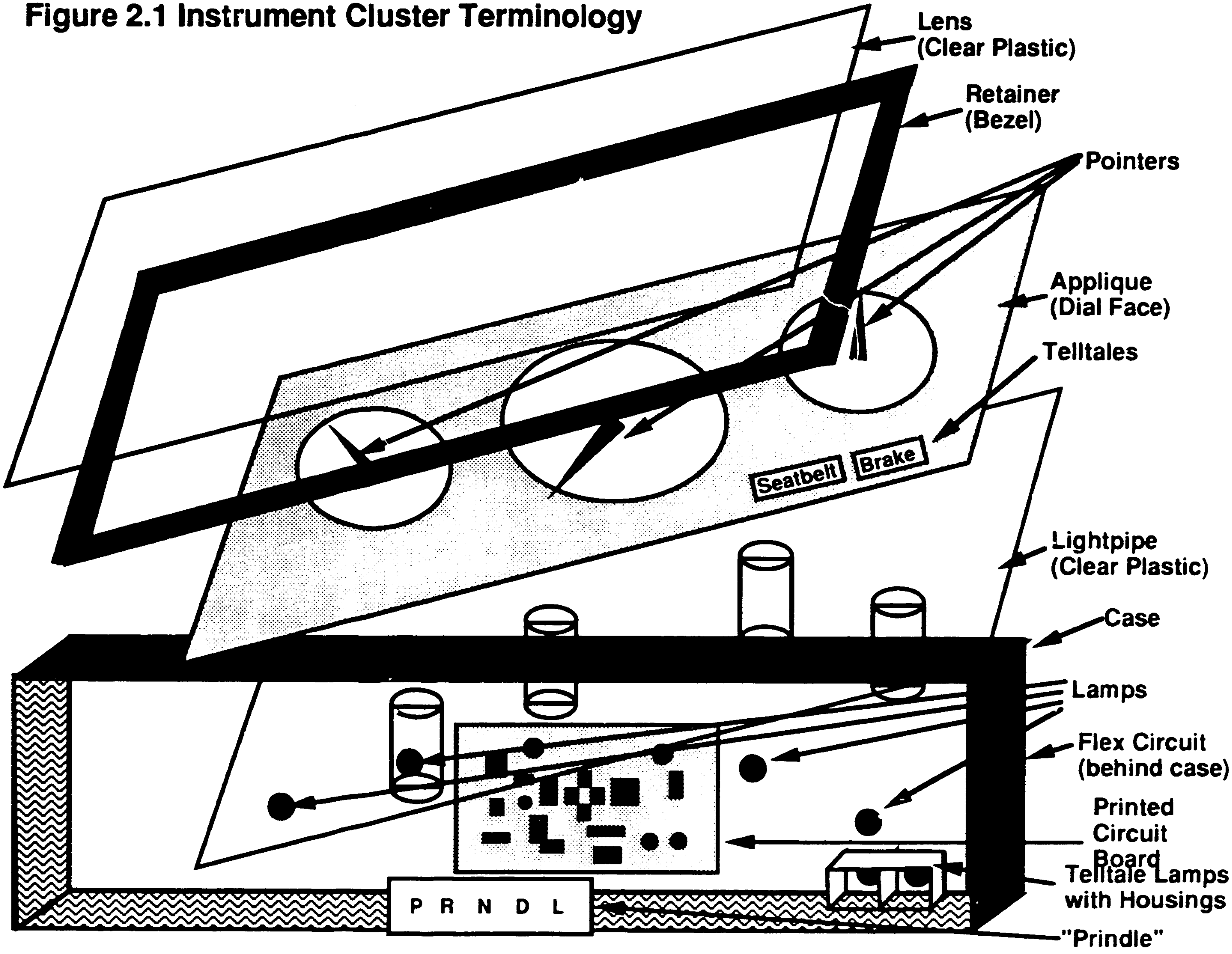
2.5 Instrument Cluster Terminology

The major parts of an instrument cluster are depicted in Figure 2.1. Starting from the front, the lens is attached to the retainer (or bezel), whose function is to keep the applique and lightpipes flush against the case. The lightpipe directs light from the lamps in the back of the case to the various dial faces on the applique, and to the pointers (through the hub of the pointer) if the pointers are internally lit. The applique is usually fastened with adhesive to the lightpipe, and the gauge mechanisims are fastened to the lightpipe with screws.

The circuit boards contain various electronic components, and may be either inside or outside the back of the case depending on the design. If the circuit board is outside the case, it is often covered with an additional back cover to provide protection from static electricity and potential handling damage. Sometimes a flexible circuit is attached to the back of the case instead of a rigid circuit board. This so-called flex circuit is a sandwich of copper laminated with mylar on which tracings have been etched. The flex circuits carry electrical signals from the off-board connector to the various gauges, lamps, and smaller circuit boards.

The telltales are warning lamps which indicate if turn signals are on, whether the parking brake is set, and so on; they consist of lamps in a chimney-shaped telltale housing (usually molded as part of the back case) which directs light from the lamp through a colored filter to the driver. Finally, the shift indicator (also known as a "prindle" from the usual sequence of letters on it (P R N D L)) is usually a separate mechanism with either a mechanical or an electrical connection to the shift control.

Figure 2.1 Instrument Cluster Terminology



Chapter 3: Process Capability

3.1 Introduction

One area of significant difference between DE and JS is that of process capability[1]. Two processes in particular differed substantially at DE and JS: applique screening and pointer staking. In the case of applique screening, both vendors scrapped a significant proportion of their output. In the case of pointer staking, the process in use at JS was significantly more capable than some of the processes in use at DE. This chapter briefly explains these two processes, examines the differences between DE and JS process capability in these two areas, and discusses the effect of these differences on product or total cost.

3.2 Applique Screening Explanation

Most dial faces on analog instrument clusters today are of two main types: painted sheet metal or silk-screened polycarbonate. Since over three quarters of all dial faces are the silk-screened type, this chapter confines its discussion of dial faces to that type.

Silk-screened dial faces consist of a polycarbonate base on which multiple layers of ink are screened. Each layer of ink may be either translucent or

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[1] Process capability is a term used to describe the relationship of the tolerance of a particular dimension or other measured quantity to the process variability of that quantity. The Process Capability Index (C_p) is often used to characterize the capability of a process, and is defined as:

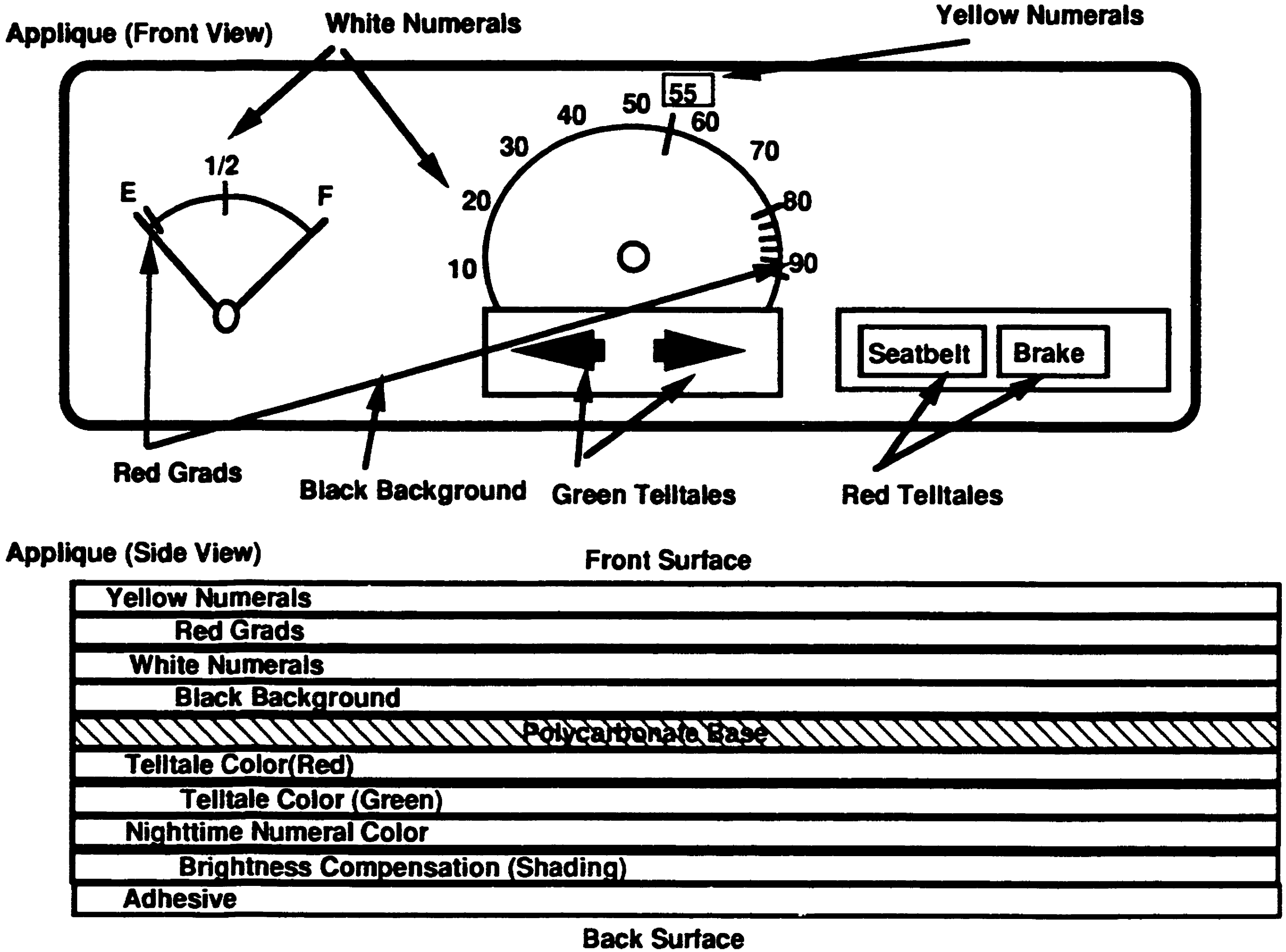
$$C_p = \frac{\text{Upper Specification Limit - Lower Specification Limit}}{6\sigma}$$

Another measure, C_{pk}, is used to characterize both the spread of the process and whether it is centered:

$$C_{pk} = \text{Min}\left[\frac{\mu - LSL}{3\sigma}, \frac{USL - \mu}{3\sigma}\right]$$

In this thesis, the phrase is also used more loosely to refer to the yield of specific processes, since process capability is intimately related to yield.

Figure 3.1 Dial Face Applique



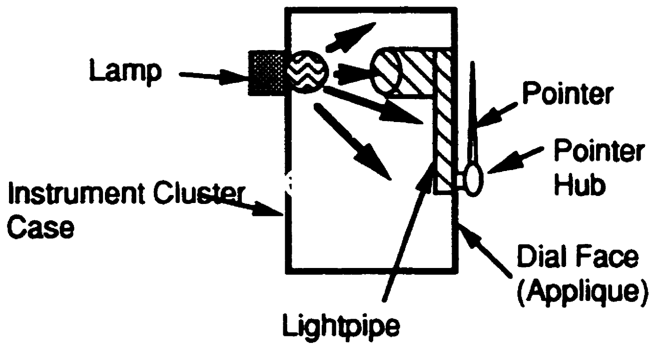
Applique (Front View)

Applique (Side View)

Figure 3.1. Applique layers. This figure shows an 9-layer applique. The layers are shown as if they cover the entire applique in order to indicate the order in which they are typically applied; in reality, most passes only cover a small portion of the surface of the appplique.

Figure 3.2 Cluster Illumination Methods

Backlit with Lightpipe for Pointer

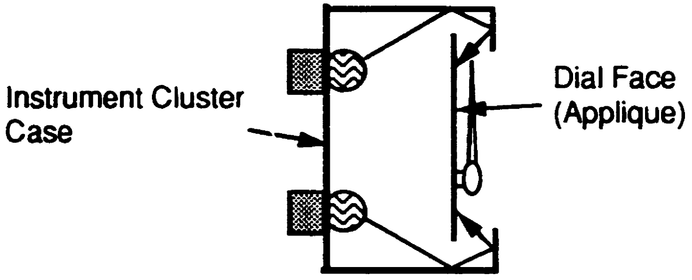


Illumination Methods
The figure at left is backlit; light passes through the applique to the driver. In addition, the pointer at left is lit through the hub; a lightpipe guides light from the lamp to the hub.

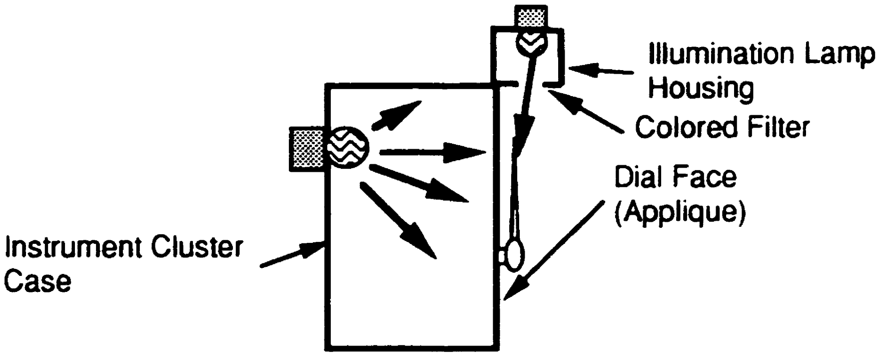
The figure at lower left is indirectly floodlit; this method is typically used for metal dial faces. Light is reflected off the retainer to the surface of the dial face, and reflected from the dial face to the viewer.

The figure below depicts a backlit applique with floodlit pointers. This type of design is popular with some Japanese manufacturers.

Floodlit(indirect)



Backlit Applique with Floodlit(direct) Pointer



opaque, though typically only the base layer is opaque. Since instrument cluster design requirements often specify that the dial face colors be different in daytime and at night, layers of ink are applied to both the front of the dial face and to the back. (See Figure 3.1.) The ink layers in front of the opaque (usually black) base layer produce the daytime colors when sunlight is reflected off the dial face, while both the front and back layers produce the nighttime colors when the dial face is backlit by incandescent bulbs.[1] (See Figure 3.2.) Up to 15 layers may be applied to a single applique.

In the silk screening process, a mask is laid on top of the applique. Ink is spread over the mask, and passes through the pattern in the mask onto the applique. When the mask is removed, the ink pattern remains. The ink is then dried using either heat or UV light.

There are two main methods for moving the applique from one silk-screening station to another. One method is a sheet-feeding method, in which individual sheets(usually about 2 feet by 3 feet) are fed through a series of ink-printing and ink-drying stages. The other method is a roll-to-roll method, where the polycarbonate base is fed through a type of web printing press. The press has both ink-printing and ink-drying stations.

In each case, dial faces are not processed individually; the number of dial faces processed simultaneously by each silk screening station varies from three at a time for large appliques to over twenty at once for smaller ones. After the last ink layer is screened onto the polycarbonate base, an adhesive layer is applied

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[1] Some dial faces are <u>floodlit</u> by shining incandescent bulbs on the dial face; in this case, the night-time color can be changed through the use of filters or colored reflective surfaces.

to the back of the applique so that it can be mounted during final assembly.[1] This layer is then covered with a plastic backing which is removed just before the applique is mounted in final assembly. A protective plastic facing is also applied to the face of the applique, and the applique is die-cut to its final shape.

3.3 Applique Screening Process Capability

As explained earlier, the appliques which are used in instrument clusters to form the dial face consist of a polycarbonate base on which up to 15 layers of ink are screened. Typically, a certain percentage of these appliques are scrapped during processing due to registration (i.e. misalignment), pinholes, damage during handling, and so on. DE engineers indicated that outside suppliers used an "industry standard" of 4 percent loss per pass for screened appliques. DE performance generally exceeds that of outside suppliers, often by a substantial margin.

Data from JS indicates that the corresponding per-pass loss rate for JS ranges from about 0.5 percent to 2 percent, depending on the product and other factors. While the difference between 98 percent yield and 96 percent yield may not seem significant, it must be remembered that this is a <u>per-pass</u> yield. The resultant difference between final yields for a 15-pass applique can be quite substantial, as Table 3.1 shows.

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[1] Sometimes the adhesive is applied during final assembly rather than during applique fabrication.

Table 3.1 Effect of Per-Pass Yield on Final Yield

No. of Passes	Final Yield @1% Loss Per Pass	Final Yield @2% Loss Per Pass	Final Yield @4% Loss Per Pass
4	96%	92	85
8	92	85	72
12	89	78	61
16	85	72	52

Note: Final Yield = $[1 - (\text{per-pass loss})]^n$

Since the cost of all units must be recovered by the good units which are sold, the cost of good units for a given process yield is:

Cost per good unit = (Cost of all units)/yield

Table 3.2 shows that the effect of improving process yield on costs is quite dramatic: cutting per-pass loss in half will result in a 8% to 15% cost reduction for 8-pass appliques, and up to a 28% reduction for more complex products.

Table 3.2 Effect of Per-Pass Loss on Applique Cost

No. of Passes	Per-Unit Applique Cost @1% Loss Per Pass	 @2% Loss Per Pass	 @4% Loss Per Pass
4	$1.04	1.08	1.18
8	1.08	1.18	1.39
12	1.13	1.27	1.63
16	1.17	1.38	1.92

Note: costs are shown for hypothetical appliques whose cost would be $1 if process yield were 100%.

Although the possible savings due to improved process yield in applique screening cannot be estimated exactly, it is nevertheless possible to estimate roughly how much could be saved through a moderate improvement in yields. Currently, appliques are roughly 12% of product costs, depending on the cluster.[1] Assuming DE I&D sales are roughly $500 million (a conservative estimate), and that costs are 90% of sales, applique costs are roughly $54 million annually. If the yield were improved enough to reduce the average cost of appliques by 10% (by reducing per-pass loss roughly 1 percentage point), DE would save $5.4 million per year.[2] Clearly, the potential benefit of yield improvement is substantial.

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[1] The actual percentage depends on the particular applique; 12% is simply chosen as a representative, if arbitrary, percentage for the sake of the calculation.

[2] Using proprietary numbers, a 25% reduction in per-pass scrap was found to result in savings from $25,000 to nearly $300,000 annually per part number for several representative part numbers.

While cost reduction is the primary benefit of improved yield, yield improvement has other benefits as well. In particular, improved yield effectively increases equipment capacity. This is significant since applique production capacity is currently fully utilized. Increases in effective capacity such as those provided by process improvement would enable DE to bring more work in-house without purchasing additional equipment or adding workers.

3.4 Pointer Staking Explanation

Pointer staking is the operation which attaches the needle (pointer) of a gauge (such as a speedometer) to the gauge mechanism. This operation involves aligning the spindle of the gauge mechanism to a hole in the pointer hub and pressing the hub onto the spindle. The two parts must be aligned within a specified angular tolerance, and often the pointer must be staked to a specified height above the face of the gauge. While this might seem to be a fairly standard process for most gauges, in practice, there are a wide variety of methods for attaching pointers. Table 3.3 outlines some of the methods currently in use at DE. Process parameters which differ from method to method include:

- Number of pointers staked simultaneously
- Machine cycle time
- Type of gauge mechanism
- Type of gauge spindle (spindle-hub interface)
- Whether the staker has a vision system, a video monitor, or no vision
- Whether the product is calibrated in the same machine or not

Table 3.3 Types of Stakers

Vehicle	Spindle Type	# Ptrs Staked	Cal '(3)	CB '(4)	Vision/ Video?	Pointer Placement	Height Contro	Staking head Motion	Comments
Vehicle A	PTH(1)	3	y	y	Video	Hand Place	Push to Stop	Cluster Pivots; Heads rise from table	
Vehicle B	PTH	3	y	n	Video	Hand Place	Push to Stop	Cluster Pivots	Same as Vehicle
Vehicle C	PTH	3	y	n		Vacuum Hea	Push to Stop	Staker head pivots down	
Vehicle D	PTH	3	y	n	None	Vacuum Hea	Push to Stop	Part staked in front of Operator	
Vehicle E	PTH	3	y	n	None	Vacuum Hea	Push to Stop	Part staked in front of Operat	Same as Vehicle
Vehicle F	T/B(2)	3	y	n	None	Vacuum Hea	Push to Stop	Staker head pivots down	Same as Vehicle
Vehicle G	T/B	1	y	n	Vision	VH	Push to Stop	Staking head pivots down	
Vehicle H	PTH	2	y	y	None	Vacuum Hea	Push to Stop	Part staked in front of Operat	Same as Vehicle
Vehicle I	PTH	1	y	y	Video	VH	LVDT Sensor	Part staked in front of Operator	
Vehicle J	PTH		y	y	None	Vacuum Hea	LVDT Sensor	Part staked in front of Operator	
Vehicle K	PTH	2x2	y	n	Vision	Hand Place	Push to Stop	Sliding Stake Head	Slides on table
Vehicle L	T/B		y	y	None	Hand Place	Pneumatic	Sliding Stake Head	Slides on ways;
							Pressure		std. air core mec
Vehicle M	T/B		y	n	None	Hand Place	Pneumatic	Staker head Pivots	
							Pressure		

(1)PTH = Push To Height
(2)T/B = Tapered Spindle/Brass Bushing
(3)Cal = Calibration Performed in Staking Machine? (y/n)
(4)CB = Circuit Board Attached?(y/n)

- How pointer height is controlled
- How the pointer is fixtured
- Whether the pointer is staked in car position or not
- Type of action of the staking head (rotary, linear)
- Whether the cluster moves to the staking head, or vice versa
- Whether the circuit board is attached before or after staking

Variations in these process parameters results in a large number of possible staking processes.

3.5 Pointer Staking Process Capability

In pointer staking, as in applique screening, the main benefit of improved process capability is reduced product cost. However, the manner in which the benefits of improved pointer staking process capability are realized are not as uniform. In some production lines, gains could be realized through increased capacity (which may reduce cost through reduced overtime); in others, labor hours could be reduced without changing capacity. In addition, improved process capability could improve customer relations by reducing staking-related returns.

On one line, DE industrial engineers estimate that up to 28 man-shifts could be eliminated by improving the pointer staking process on that line. Roughly two-thirds of this reduction would be due to increased throughput on the line, while one-third would be due to reduced rework on the same line. (See Table 3.4) Admittedly, this is a relatively high-volume line, whose process capability is significantly worse than average, but even on lower-volume, more process-capable lines, DE engineers estimate that a 5-10% capacity improvement is possible (without increasing labor hours or adding equipment) through improved first-time yield and reduced rework.

Table 3.4 Potential Savings on High-Volume, Low-Capability Line

Reduction in Line operators:	20 man-shifts@$60,000/yr
Reduction in Salvage Operators:	8 man-shifts@$60,000/yr
Total:	28 man-shifts@$60,000/yr =
Monetary Savings:	$1.68 million/year

Potential Improvement: Annual savings of $1.68 million

If we again try to estimate the potential savings which could be realized in final assembly areas throughout the plant if process capability were improved, the results are as follows. Denoting total final assembly costs as T, per-unit costs as C, production volume as Q, material as M, direct labor as D, indirect labor as I, and other overhead (equipment, etc.) as O, we have:

$$T = C \times Q = M + D + I + O$$

If we want to increase volume 5% without improving process capability, the costs will be 5% greater:[1]

$$1.05 \times T = C \times (1.05 \times Q) = 1.05 \times (M + D + I + O)$$

---

[1] This analysis assumes that the process is scaleable, a reasonable assumption for labor but an admittedly weak one for equipment.

After improving the process, we can produce 5% more Q (a conservative estimate) by buying 5% more M but without adding additional labor, equipment, or overhead.[1] Therefore,

$$T' = C' \times (1.05 \times Q) = (1.05 \times M) + D + I + O$$

Compared to what it would have cost to produce this quantity without improving process yield, the savings are:

$$\Delta T = (1.05 \times T) - T' = [1.05 \times (M + D + I + O)] - [(1.05 \times M) + D + I + O]$$

$$= 0.05(D + I + O)$$

In other words, potential savings are 5% of direct, indirect, and overhead expenses in the final assembly area.

Assuming again that costs are 90% of I & D sales of \$500M, and that final assembly direct, indirect, and overhead expenses are 60% of costs, of which half are in final assembly,[2] we have

Total costs = 90% x \$500M = \$450M

D+I+O = 60% x 1/2 x \$450M = \$135M

Potential Savings: 5% x (D+I+O) = \$6.75M

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[1] Although there may be some transition costs for DE, the fact that JS staking processes are more capable but not substantially more labor or capital intensive is taken as evidence that it is possible for DE to achieve a more capable position without adding labor, overhead, or equipment.

[2] The actual percentage depends on the particular cluster; 60% is simply chosen as a representative, if arbitrary, percentage for the sake of the calculation.

It should be noted that these savings may not be easily realized. If the capability of existing equipment could be improved at minimal cost, savings could be realized by reducing direct and indirect labor, but the additional equipment capacity will simply become unused capacity and therefore overhead would not decline. In addition, since improving process yield may involve significant expenditures if applied to existing equipment, it is likely that the savings would be achieved as improved equipment replaces existing equipment through the introduction of new models to replace old ones.[1] The savings figure above is best understood as an estimate of the difference in costs between DE operating near current sales levels with a less than 100% capable staking process and DE operating at the same sales level with a 100% capable process.

Examination of JS staking practices confirms that improvement of staking process capability is possible. JS appears to have virtually no rejected gauges due to staking failures. Differences between DE and JS with respect to gauge staking include both process differences and product design differences. Process differences include the practice of individually staking those gauges for which accuracy is critical, i.e. speedometers and tachometers; different staking forces; charging of magnets after pointers are staked; and the use of alignment fixtures which are less operator-dependent than those used at DE. Design features that differ include features which enable JS to use greater staking force than DE, and the use of offset and gain potentiometers in speedometer and tachometer circuits.

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[1] Roughly 20% of DE instrument clusters are replaced by new models each year.

Non-Monetary Benefits. In addition to the increased capacity to be gained from improved pointer staking capability, improved capability could also improve relations with DE customers, both within GM and outside. An examination of recent returns from GM assembly plants shows that staking errors account for substantial proportion of plant returns. Table 3.5 shows the proportion of returns due to staking errors for several representative line.

Table 3.5 Potential for Reduced Pointer Staking Plant Returns

Car Line	% of Returns due to Staking	% of Returns due to Staking or Calibration
Vehicle A	33	33
Vehicle B	8	10
Vehicle C	7	11
Vehicle D	3	3

Reduced scrap is yet another possible consequence of improved process capability. However, as Table 3.6 shows, the potential savings in this area is not particularly significant.

Table 3.6 Potential for Reduced Pointer Staking Scrap

Car Line	Avg. Monthly Scrap Pointers	Avg Monthly Scrap - CBCs/Gauge Asm.
Vehicle A	$727	19
Vehicle B	386	236
Vehicle C	583	1852
Vehicle D	10	587

3.6 Relationship of Decisions to Available Cost Information

In examining the choices made by DE engineers in, for example, applique design, the difficulty of making decisions which involve multiple departments is a recurring theme.[1] One example which illustrates this point is the decision on a particular vehicle to eliminate die-cut adhesive on the applique.

In this particular cluster, the DE design engineer initially specified that the applique was to have a die-cut adhesive backing, so that only the areas of the applique which contacted the lightpipe would have adhesive. (Other areas, such as telltales, are exposed on the back and consequently need no adhesive.) However, die-cutting the adhesive can cost as much as 50¢ more per applique than uncut adhesive, and as a result the applique production department persuaded cluster engineers to eliminate the die-cutting requirement. The die-cutting requirement was subsequently eliminated as a cost-saving measure. However, dust contamination of the exposed adhesive on the applique results in substantial scrap and rework in the final assembly department. The costs of eliminating the die-cutting operation are summarized in Table 3.7. Rather than saving cost, elimination of die-cutting the adhesive may actually increase cost, since it causes the final assembly area to waste time assembling product which is subsequently scrapped[2]. This example illustrates

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[1] Decisions involving several organizations are even more problematic. For example, DE and its customers chose to replace mechanical speedometers with electro-mechanical ones in large part because of reliability concerns. The low reliability of mechanical speedometers is due to a great extent to the difficulty of establishing a speedometer cable routing through the vehicle which will not cause kinks in the cable, since this is the primary failure mode of mechanical speedometers. Here again, the difficulty of cross-organizational coordination drives design choices.

[2] Whether the elimination of die cutting is economical or not depends on the exact proportion of applique scrap due to dust; this data was not available. Anecdotal evidence from the production area suggests, however, that well over half of the scrapped appliques were scrapped due to dust contamination.

not only the difficulty of making a multi-department decision, but also the difficulty of incorporating all relevant process considerations into design standards.[1]

Figure 3.7 Estimated Vehicle X Applique Costs Without Die-Cut Adhesive

Item	**Low**	**High**
Scrapped Applique	$3.00	5.00
Scrapped Pointer(s)	0.40	1.20
Wasted Labor	2.70	3.20
Total	6.10	9.40
(per scrapped part)		

Breakeven Scrap Rate @ $0.50/applique: 5-8%

Actual Scrap Rate: 13%*

*Current Vehicle X Scrap Rate for Relevant Appliques (total scrap, including non-dust-related scrap)[2]

There are other areas in which the limited availability of information distorts the decision-making process by hiding the costs of certain options. For instance, the minimum distance between features (especially between features which are different colors) plays a key role in determining the scrap rate for dial face appliques. However, when applique costs are estimated, such design details

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[1] See Chapter 5 for a more thorough discussion of the relationship between product and process design standards.

[2] Whether die-cutting the adhesive will save money depends on the proportion of scrap due to dust. Unfortunately, this data was not available, although production operators estimated that dust caused well over half of the applique scrap on this line.

are not considered; rather than estimating the specific scrap rate for a particular applique and factoring that rate into the cost, an average scrap rate is applied. The result is that customers have no incentive to choose a more manufacturable design, since there is no reward for doing so (and no penalty for choosing a difficult-to-manufacture design).

The same holds true for warranty data. Although any programs for which warranty costs are significantly above average receive attention at DE, warranty costs are not tied to specific clusters; instead, they are allocated along with other overhead expenses (including engineering expenses). The effect of allocating these costs is to focus the attention of design engineers on piece-part cost (that is, the cost of individual parts) at the expense of other considerations.

Although the above discussion suggests that warranty and scrap costs should be forecast and figured into the cost of the product prior to the completion of product design, this may in fact not be the most effective way to focus attention on these aspects of quality. Not only are these costs difficult to estimate, but the emphasis should be on reducing these costs rather than estimating them. Consequently, there may be other, more effective and less time-consuming and cumbersome methods of focusing attention on these aspects of product quality.

3.7 Summary

The above analysis suggests that improvements in process capability could conservatively save DE over $12 million per year. While the gains in applique process capability can be realized immediately (because all available applique processing capability is being used currently), the gains in staking will not be fully realized unless volume increases.

While the above analysis suggests the magnitude of the potential savings, it does not suggest how to achieve those savings. The next chapter discusses the role of design standards and process standards in the execution of a design philosophy. The use of standards, discussed in Chapter 5, is one way to improve process capability.

Chapter 4. Design Philosophy

4.1 Introduction

In examining the designs produced by various instrument cluster makers, an observer is struck by the wide diversity of designs which can be created to fulfill the same basic function, namely, the provision of vehicle information to the driver. Nevertheless, within both DE and JS, there are broad categories of features for which the DE designs consistently differ from JS designs. These differences are taken to be indicative of differences in the design philosophies of DE and JS. This chapter discusses some of the visible and less-visible differences between DE and JS design philosophies as well as the rationales behind those differences and some of the consequences of those differences.

4.2 Product Design Philosophy

As noted in Chapter 2, there is an astonishing variety of ways of communicating vehicle status information to the driver. Clusters may differ by customer, content, display technology, style, or speedometer type. While some of these differences are readily identified by the customer, others are not visible differences.

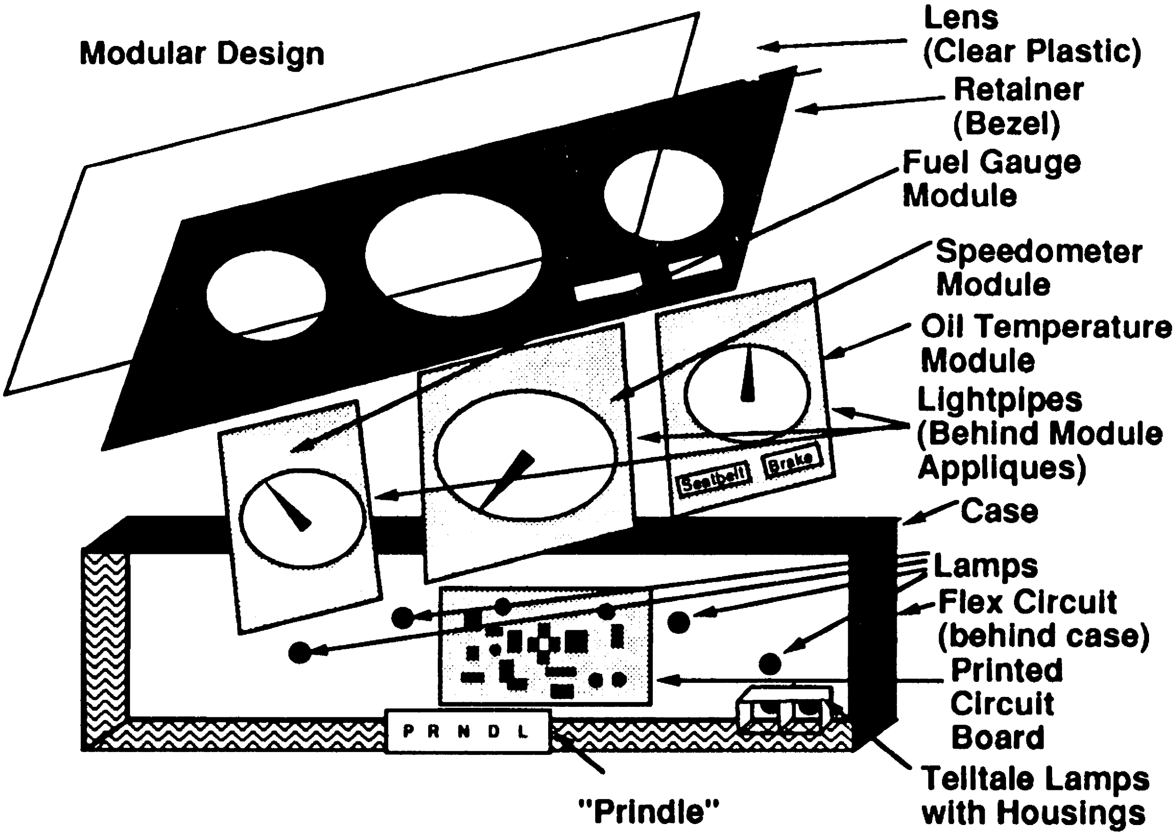
These other differences, though unseen, may be critical to the manufacturer. For instance, a "modular" style cluster may consist of several subassembly modules linked together, or a single gauge subassembly covered by a retainer which divides the gauges visually into "modules". Manufacturers may choose different methods of fastening parts together; different divisions of functions into parts and subassemblies; different materials for the various parts of the cluster.

The process of specifying the design for an instrument cluster involves a complex interplay of styling, cost, and manufacturing capability issues. The design decisions embodied in a particular design are the result of the design team's efforts to satisfy the relevant constraints. Moreover, these decisions are affected by past decisions, and in turn affect future design decisions. Both product style and manufacturing capabilities are developed over a long period of time, and change in these areas is typically evolutionary rather than revolutionary. The guidelines and organizational preferences, either formal or informal, which simplify design decisions by encouraging a particular choice, are called design philosophies in this thesis. As a result of differences in both design philosophy and manufacturing capabilities, product designs developed by different organizations to meet the same functional specification may differ substantially.

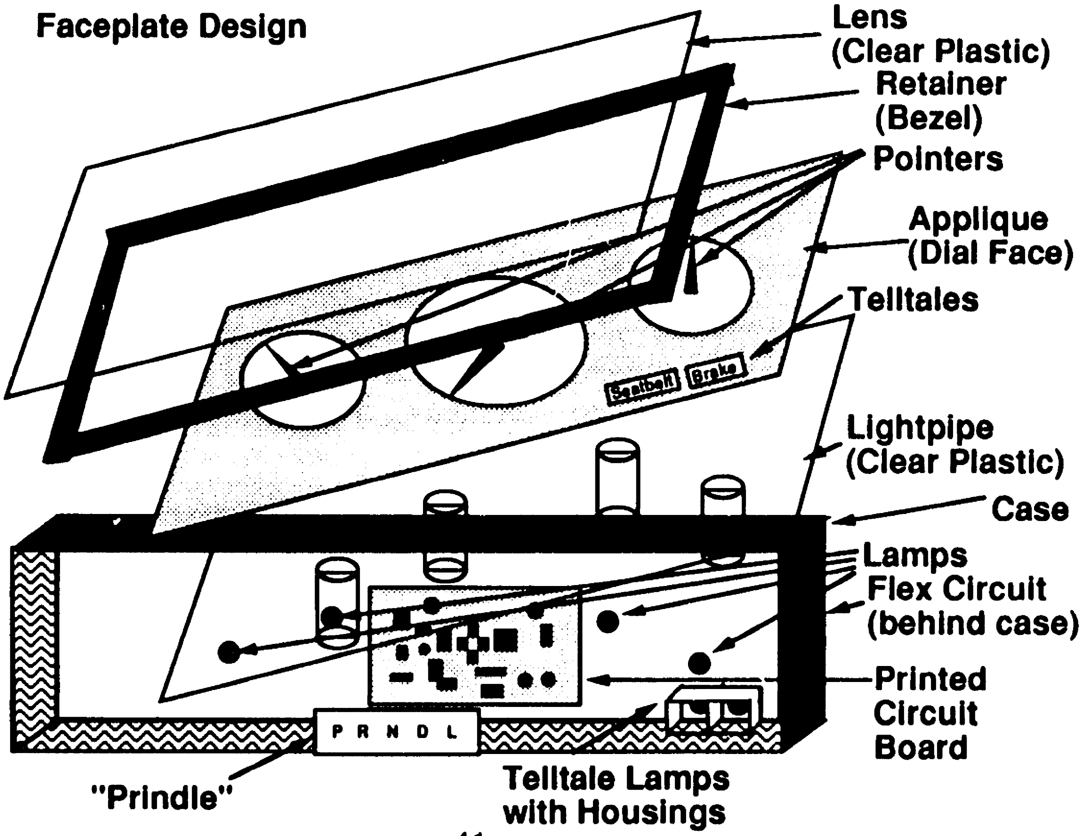
As a result of both the styling preferences of their customers and of the history of their manufacturing processes, the design philosophies of DE and JS are quite distinct. This chapter will examine differences in product design philosophy with respect to:

- Product Modularity
- Use of Screws
- Colored Telltale Design
- Tooling Considerations

Figure 4.1 Modular and Faceplate Designs



Modular Design



Faceplate Design

4.3 Product Modularity

One of the first differences to strike an observer of DE and JS clusters is the consistent use of modular designs by JS. (Here the term "modular" is used to describe designs where the gauges are built up as separate subassemblies rather than a single large subassembly. See Figure 4.1.) While DE sometimes uses modular designs, their use is by no means universal, and in most cases, DE engineers prefer a so-called "faceplate" design.[1] In a faceplate design, all gauge mechanisms are attached to a single lightpipe, and a single applique containing all dial face graphics (and usually, most telltale filters) is attached to the lightpipe. DE engineers usually cite cost as the main reason for preferring faceplate designs, noting that such designs:

- have fewer lightpipes, and therefore require fewer molds, and
- have fewer parts to handle, and are therefore less susceptible to handling damage.

In addition, faceplate designs cannot have light leaks between modules as modular designs can.

On the other hand, JS engineers strongly prefer modular designs to faceplate designs. In their view, modular designs are superior from a cost, quality, and overall manufacturability standpoint.[2] The reasons for their preference for modular designs can be grouped into five categories:

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[1] DE engineers are often driven to this preference by DE customers, who also generally prefer the flat appearance of the faceplate design.

[2] It should be kept in mind that JS engineers' preferences are biased by their own design philosophy and manufacturing organization.

Susceptibility to Damage. Compared to the small subassemblies used in modular designs, the single large applique used for faceplate designs is difficult to handle. Small appliques and lightpipes are strong enough to support gauge mechanisms on their own, whereas faceplate-sized parts are relatively weak in comparison to their weight. Consequently, large appliques are more likely to be damaged, and when damaged, the entire applique (which is large and expensive) must be replaced. In contrast, if a modular applique (or lightpipe) is damaged, only a relatively small part is scrapped.

Part Costs. The size of the applique means that larger, more expensive fixtures are required; this also increases the cost of the product. In addition, a large applique tends to have a lower yield than a smaller one.

Ease of Assembly and Service. The faceplate design is more difficult to assemble and assembly tasks are more difficult to balance, in part because assembly sequence is not as flexible. Moreover, access is difficult, both for speedometer and tachometer calibration, and for magnet charging.[1]

Flexibility. The modules used in modular designs are usually the same basic shape, and as a result, the fixtures are less product-specific. Often, current production equipment (such as

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[1] These considerations apply to JS gauge and circuit designs, but are not relevant for DE designs.

gauge magnetizers) for modular units can be used to make service parts for non-current production.[1]

Ease of Fabrication. Finally, the large lightpipes required by faceplate designs are difficult (and slow) to mold; modular designs have smaller, simpler lightpipes, which can be molded quickly and relatively easily on smaller, cheaper equipment. The additional tooling cost, which results from having to make multiple lightpipes for a modular design, can be partially offset through the use of multi-cavity molds.

In short, while DE has not established a clear preference regarding product modularity, JS has chosen to use modular designs rather than faceplate designs, and then developed fabrication and assembly techniques which capitalize on the advantages of that choice.

4.4 Use of Screws

A second, striking contrast between DE and JS designs is not visible to the average driver, but is readily apparent when the instrument cluster is removed from the vehicle. Specifically, DE designs use relatively few screws, while the JS design uses dozens, including five for each gauge in the cluster, three in back and two in front. The DE gauge design uses none in back and two in front.

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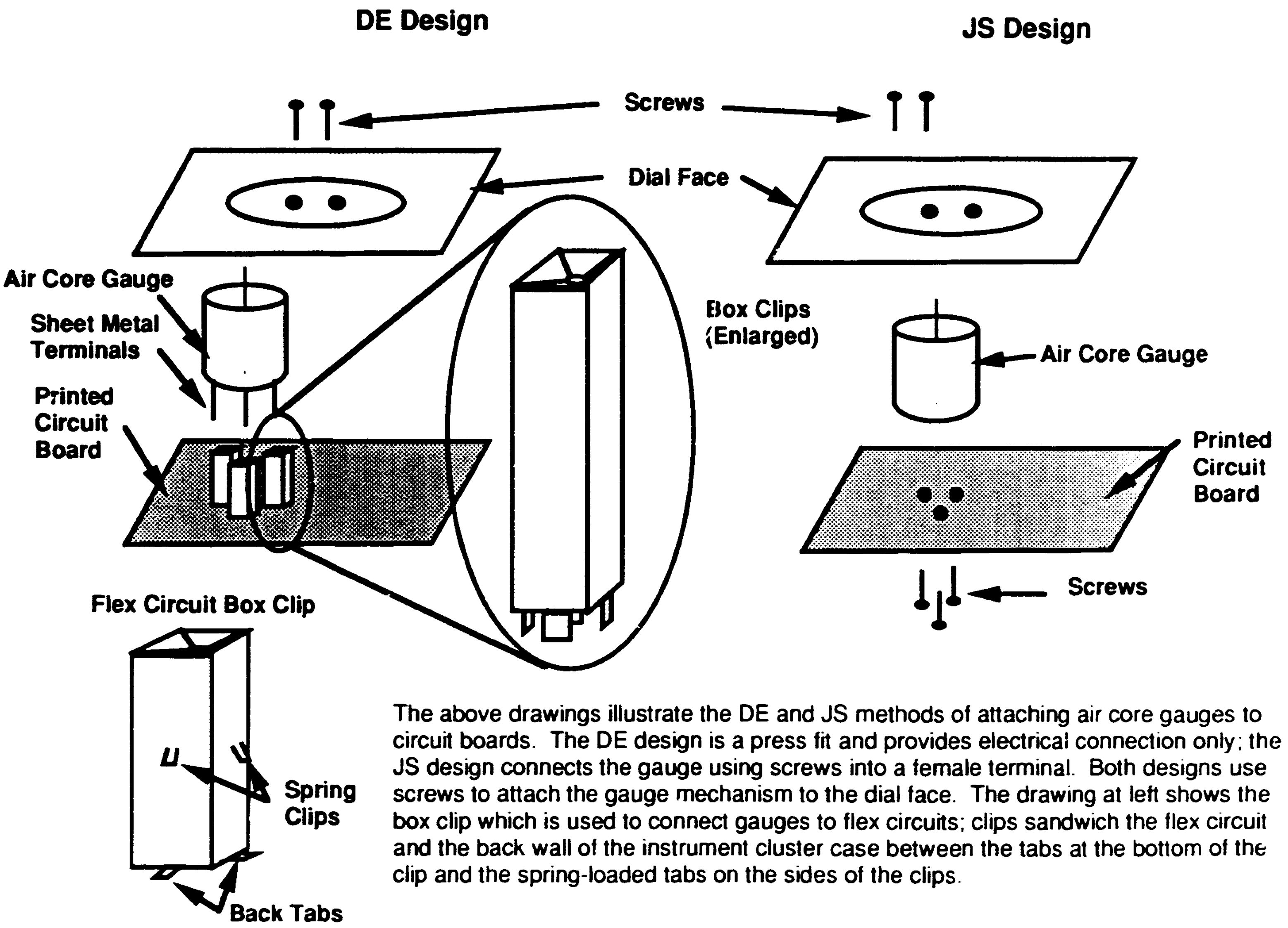
[1] For an excellent discussion of this topic, see the MIT LFM 1991 thesis by Tom Taylor, MSME, MS Mgt.

Figure 4.2 Air Core Gauge Terminal Designs



The above drawings illustrate the DE and JS methods of attaching air core gauges to circuit boards. The DE design is a press fit and provides electrical connection only; the JS design connects the gauge using screws into a female terminal. Both designs use screws to attach the gauge mechanism to the dial face. The drawing at left shows the box clip which is used to connect gauges to flex circuits; clips sandwich the flex circuit and the back wall of the instrument cluster case between the tabs at the bottom of the clip and the spring-loaded tabs on the sides of the clips.

(See Figure 4.2.) In this instance practices are clearly different, and each group vigorously defends its methods. Why have the two organizations diverged?[1]

The answer is found in the companies' approaches to assembly automation. DE has traditionally driven screws with hand-held screwdrivers, and for an operator, manually driving screws is a fatiguing, error-prone activity.[2] In comparison, pushing gauge terminals into so-called "box clips" is a relatively easy task for production workers. JS, on the other hand, has extensive experience with robotic screw-driving, and has relatively inexpensive, reliable equipment to perform this task.

The comparison of box clip and screws for connecting gauges to their circuits has another dimension as well. At DE, the use of box clips to connect gauges to circuits rather than screws may simply substitute one difficult task for another. Although the connection of box clips to gauge terminals during final assembly is relatively straightforward, the connection of box clips to flex circuits (flexible pieces of plastic sheets on which copper circuits are etched) can be problematic.[3] Current DE designs sandwich the flex circuit in between the case and the back end of the box clip. The product is assembled by inserting the box clip through a hole in the flex circuit and a hole in the instrument cluster case; the clip snaps in place, and therefore the thickness of the case at the hole is a critical dimension. As in many Design-for-Assembly(DFA)-driven designs,

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[1] The previous DE design used male threaded terminals with nuts to make electrical connections. The nuts were prone to loosening due to thermal cycling, and were therefore avoided in the new design. (JS avoided this problem by using screws with captive lockwashers.)

[2] Screwdriving can also lead to chronic wrist problems (such as carpal tunnel syndrome) if not done properly.

[3] This is not an issue for printed circuit boards, since box clips are more easily inserted into rigid circuit boards than into flex circuits.

in this case the substitution of a snap fit-part for a screw makes assembly easier, but puts more stringent dimensional requirements on the mating parts.

To summarize, in the use of screws, JS has developed an automated process to minimize the disadvantage of screws, while DE has pushed the difficulties involved in fastening gauges to circuits upstream, into fabrication. Once the upstream processing difficulties are solved, the result may be superior to the JS design, but until then, JS has an edge in its proven design and process.[1]

4.5 Use of Separate Telltale Filters

The design of colored telltales provides another example of a difference in design philosophy. While DE engineers usually design the filters as a part of their applique, JS engineers usually design a separate, molded plastic color filter to provide the color for a telltale, using the applique only for the outline of the telltale.[2] DE engineers note that their design has many fewer parts than a comparable JS design (since a cluster can have over a dozen telltales); JS engineers respond that their designs are much less susceptible to light leaks, since in the JS design, the telltale filter is recessed into the case.[3] However, the engineers' preferences are only a partial explanation. The JS engineers are responding to the availability of second-tier suppliers who can insert the colored plastic filters into the cases relatively cheaply; DE engineers are responding to

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[1] It is interesting to note that the JS design has evolved in small increments from its prior design, while the DE design development has been more revolutionary.

[2] Interestingly, these designs may be converging; a recent JS design uses a silk-screened part for several telltale filters of different colors, thereby reducing the parts count without substantially increasing the likelihood of light leaks.

[3] Light leaks occur when the telltale housing and the telltale filter(or applique) do not mate properly. If the telltale filter(or applique) is not flush against the housing, light from one telltale lamp may illuminate another telltale or another part of the instrument cluster. This type of defect is called a light leak. It is especially likely to occur if a telltale stays on for a long time, since the lamp heats a small portion of the applique and causes it to distort.

a system in which such outsourcing is difficult to do, and in which many small parts are difficult to manage reliably.

The JS preference for modular design may provide another incentive to use a separate part, since screening the telltale color onto the dial face applique adds one or more operations to several parts, driving up their costs. In contrast, adding telltale colors to DE faceplate designs adds one operation per color to only one applique(since the entire dial face is one piece). If the telltale color is already needed for some other reason (such as the amber warning zone for a gauge), the telltale is essentially "free," since it adds no additional operations.[1]

If, however, the telltale color is only needed for the telltale, a different story emerges. Suppose, for example, that an engineer is considering whether to include four colored telltales(red, green, blue, and amber) on an applique which would cost \$10 without telltales. Since each additional color adds one operation, the yield of the four additional steps would be Y^4, where Y is the per-pass yield. If per-pass yield is 98%(i.e., 2% loss per pass), the yield for four steps is $(0.98)^4 = 92\%$. The resultant applique cost for good appliques (which must absorb the cost of scrapped appliques) would be \$10 * (1/(0.92)) = \$10.84. In other words, if a four-color telltale filter could be produced and installed for less than \$0.84, the parts should be made separately. If the applique is being produced by an outside vendor whose per-pass loss is 4%, the filter could cost up to \$1.77 (installed) before it became uneconomical, since \$10 * $(1/(0.96)^4)$ = \$11.77.

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[1] Since DE applique fabrication equipment can screen several colors onto the applique in one pass, DE engineers also consider a color "free" if it does not cause an additional pass through the screening press.

In telltale design, as in fastener selection, both DE and JS are responding to the economic incentives of their existing production systems. JS has chosen a conservative design approach in order to ensure reliable performance, while DE has chosen a design which minimizes assembly steps according to standard DFA criteria.

4.6 Tooling Considerations

The design of instrument cluster cases provides another example of design philosophies which have significant implications for product costs. Put briefly, JS prefers *planar* designs, that is, designs in which both the front and back surface of the case are in one plane, and both front and back planes are parallel to each other. In addition, wherever possible, the mounting bosses (used to attach the instrument cluster to the the vehicle) are in the same plane as the front of the instrument cluster case. This design preference enables JS to use *extremely* simple fixtures to hold the instrument cluster. The fixtures are essentially flat steel plates with pins used to locate the cluster on the plate.[1] The fact that the cluster is planar also means that it is easier to automate final assembly, since most operations, such as lamp insertions or screwdriving operations, are performed along a single axis normal to the plane of the case. This fact enables JS to use relatively simple automation for many operations, and also increases the likelihood that automation can be re-used for subsequent (planar) products.

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[1] When it is not feasible to keep the back of the case in one plane, JS sometimes creates cases in which the back of the case consists of several parallel planes at different levels. In this case, simple tooling can be constructed by putting thin steel plates on top of a base plate, so that all surfaces are resting on a flat steel plate.

The use of planar designs also simplifies the tooling required to mold the case, resulting in additional savings. For example, in the case design for a recent DE product, the telltale housings and other holes were not perpendicular to the front of the case. As a result, the core pulls on the case mold were relatively complex; one engineer estimated that this feature added 20-25% to the cost of the mold. Use of planar designs avoids this expense.

In summary, JS has established the planar design as the design of choice for its instrument clusters, and it has managed to convince its customers that this design will meet their requirements at an attractive cost. DE may realize the cost implications of non-planar designs, but it has not articulated them as fully, and has had less success in convincing its customers to use planar designs consistently.

4.7 Relationship of Design Philosophy to DFA Methodology

While a well-chosen design philosophy may follow traditional design for assembly (DFA) guidelines such as those suggested by Boothroyd and Dewhurst,[1] a good design philosophy does not work from theoretical considerations alone. Rather, design philosophy is much more effective if it takes into account manufacturing capabilities of the producing organization. In both their telltale designs and their gauge terminal designs, JS engineers have chosen a conservative design in order to ensure a capable manufacturing process. From a theoretical DFA standpoint, both separate telltale parts and

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[1] Geoffrey Boothroyd and Peter Dewhurst. Product Design for Assembly. Wakefield, RI: Boothroyd Dewhurst Inc., 1987

screws are undesirable, but JS deliberately chose to use these elements in their design.[1] The result for JS is an effective design philosophy.

4.8 Summary

The above examples illustrate the concept of design philosophy, a set of preferences which bias the choices made by design engineers. A well-chosen design philosophy can affect product cost both directly and indirectly, through capital costs and process yields.

At JS, the link between product design and process is clear. Design philosophies are clearly articulated, and they take into account the processes required to fabricate and assemble the chosen designs. New processes are developed in conjunction with new product designs to ensure that the new designs are manufacturable.

At DE the link between products and processes is less clear. Design philosophies are not as sharply defined, and as a result, engineers have less guidance for process development. In addition, DE product designs have been influenced by theoretical DFA considerations without adequate regard for process requirements. The result has been elegant designs that are expensive or difficult to build properly.

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[1] Other considerations may also have influenced the use of screws in JS designs. Two possibilities are: 1. Lead time considerations (since simplifying plastic molded parts by using screws can cut the mold-making lead time), and 2. Environmental considerations (since the screws fasten the gauges to the circuit board more securely than box clips). The gauge terminal screws also cleverly serve to connect the gauges to the circuit boards both electrically and physically.

Ch. 5 Product & Process Standards

5.1 Introduction

A visitor to JS is struck by the high degree of uniformity in JS designs and processes. While DE may have design guidelines for products and processes, they are less uniformly executed at DE than at JS. This chapter discusses the effects of product and process standards on product cost as well as methods used by JS to enforce those standards. It also illustrates the interdependence between product design standards and process standards at JS.[1]

5.2 Product Design Standards

The current state of DE design standards is well illustrated by the case of applique design standards. In this aspect of design, DE has standards, but they are not widely used. Although the standards specify maximum applique dimensions, minimum feature sizes, maximum spacing between colors, and so on, many appliques are designed without reference to these standards.

The impact of violating these standards can be dramatic. In one case, the yield of two appliques was compared. Although the appliques look very similar, there are subtle differences: one was wider than the other (and wider than the standard maximum width), the tolerance between different colors is different, and so on. In this case, the yield for the applique which violates the design standards is 25 to 50 percent worse than the yield of the applique

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[1] It should be noted that the ability of JS to establish and enforce such standards depends on their ability to persuade their customers to adopt such standards and stay with them.

which does not. As a result, the cost of the non-standard applique (in terms of resources used to make it) is up to twice that of the standard applique.[1]

5.3 Process Standards

The degree of process standardization at DE was also less than that of JS. While JS had at most two different staking processes for a given type of gauge, DE had nearly a dozen. (See Table 3.1.) As a result, DE is less able to develop any given staking process, and improvements made to one process may not apply to other processes.

Given this situation, it is not surprising that the average process capability of DE staking processes is below that of JS. The cost implications of inadequate process capability have already been discussed. (See Chapter 3.)

The implications of standardization on equipment cost may be illustrated by one example at DE where two very identical pointer stakers were made for different programs. Because the design was carried over from the first program, the later staker had no design engineering costs and minimal engineering support costs. The costs of the first and the later staker are noted in Table 5.1 below.

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[1] The cost system at DE did not reflect this difference because the system uses an average scrap rate for <u>all</u> appliques rather than a product-specific scrap rate.

Table 5.1 Staker Costs for Two Standard Stakers

Item	First Staker Cost*	Later Staker Cost
Design	$5,600	0
Construction		
Electrical	27,000**	27,000**
Mechanical	8,200	8,100
Installation	4,100	4,100
Engineering Support	5,400	400
Total	**50,300**	**39,600**

* The first staker was actually one of a pair; if it had been a single staker, design engineering and engineering support would have been roughly double the levels shown.

* * Electrical panel costs have been adjusted to account for discrepancies in reported material usage.

5.4 Matching Design Philosophy to Process Requirements

The staking process selected by JS provides an interesting case study in the matching of process requirements to design philosophy. To put it briefly, JS has selected a modular staking process to fit their modular product design. For speedometers and tachometers, which are usually separate modules, JS has selected a single-spindle staking process. For auxiliary gauges, which are usually in two-gauge modules, the JS staking process accomodates two pointers simultaneously. Moreover, the distance between the two staking heads can be changed. As a result, the JS pointer stakers are very flexible, and often re-usable from one program to the next. The modularity of the JS designs supports the modular JS manufacturing process choice, and vice versa.[1]

5.5 Methods of Enforcing Standards

JS has organized its standards into several standards manuals, including a Design Engineering standard, a Process Engineering standard, and an additional Quality standard for miscellaneous quality-related issues. The design engineering standard is the product design manual describing the accumulated product knowledge of JS. It includes material selection guidelines, standard tolerances, and past design mistakes which should not be repeated. The process engineering manual includes equipment standards and past processing problems which should be avoided. The quality standard manual describes problem reporting systems, qualification procedures for production lines, inspection procedures, and so on.

The JS Quality Standard is interesting not so much for what it contains as for how it is used and updated. JS calls this system their "Trouble Recurrence Prevention System." Any detected problem, whether found before or after production starts, is described in a standard form, in which the problem, its causes, and

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[1] For a more extensive discussion of flexibility in manufacturing processes, see Thomas Taylor, Evaluating and Selecting Manufacturing Flexibility, Masters Thesis, Mechanical Engineering and Management (Leaders for Manufacturing Program), MIT, 1991.

the solution applied are described. The form is then filed in a "problem history" section of the appropriate manual or manuals.

These manuals are referred to at the start of every new program: in addition to performing FMEA(Failure Mode and Effect Analyses) and FTA(Fault Tree Analyses), engineers select relevant aspects of the "problem history" manuals and describe how they will prevent the same problem from occurring in their program.[1]

In short, JS uses their standards system as a way of capturing the learning that occurs as part of the problem-solving process. This practice also ensures that: 1. all engineers are using the best known technique, which in turn ensures that any future improvements will be applicable to multiple products and processes, and 2. all engineers must agree on the best process, which forces engineers to agree on criteria used to evaluate processes and products, and then prove that their "improvement" is in fact better than the current standard.

5.6 Summary

The above discussion shows the importance of product and process standards to process capability, and the manner in which product and process standards can be chosen to enforce the linkage between product design and manufacturing capability, that is, the design

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[1] FMEAs and FTAs are tools used to determine possible errors or weaknesses in a new design. In FMEAs, possible types of failures are listed and classified by severity, and possible countermeasures are devised; in FTAs, possible low-level faults are assembled into a hierarchy connected by logic gates (ANDs, ORs, and NOTs), to determine if a combination of low-level faults could cause a major failure.

philosophy. The JS "Trouble Recurrence Prevention System" provides an example of a way to effectively disseminate process knowledge within an organization.

Chapter 6. Development Process

6.1 Introduction

The process used by DE and JS to develop new instrument clusters differs in several respects. Most significantly, JS appears to begin cutting its hard tooling substantially later in its programs than DE does. This chapter examines the advantages and disadvantages of beginning hard tooling late in a program. It also discusses what capabilities are necessary for DE to be able to start hard tooling later.[1]

6.2 DE Development Process

Figure 6.1 illustrates the DE development process for instrument clusters at a macro level. Broadly speaking, DE starts with a styling drawing from their customer (usually from the Design Staff), as well as the dimensions of the space within which the instrument cluster must fit as determined by platform engineering (CPC, BOC, or GM Truck & Bus Division), the location of the "eye ellipse" (i.e. the expected location of the driver's eyes), and various business data, such as cost targets, forecast volume, etc. DE may mock up a concept sample (which is usually non-functional), or it may proceed

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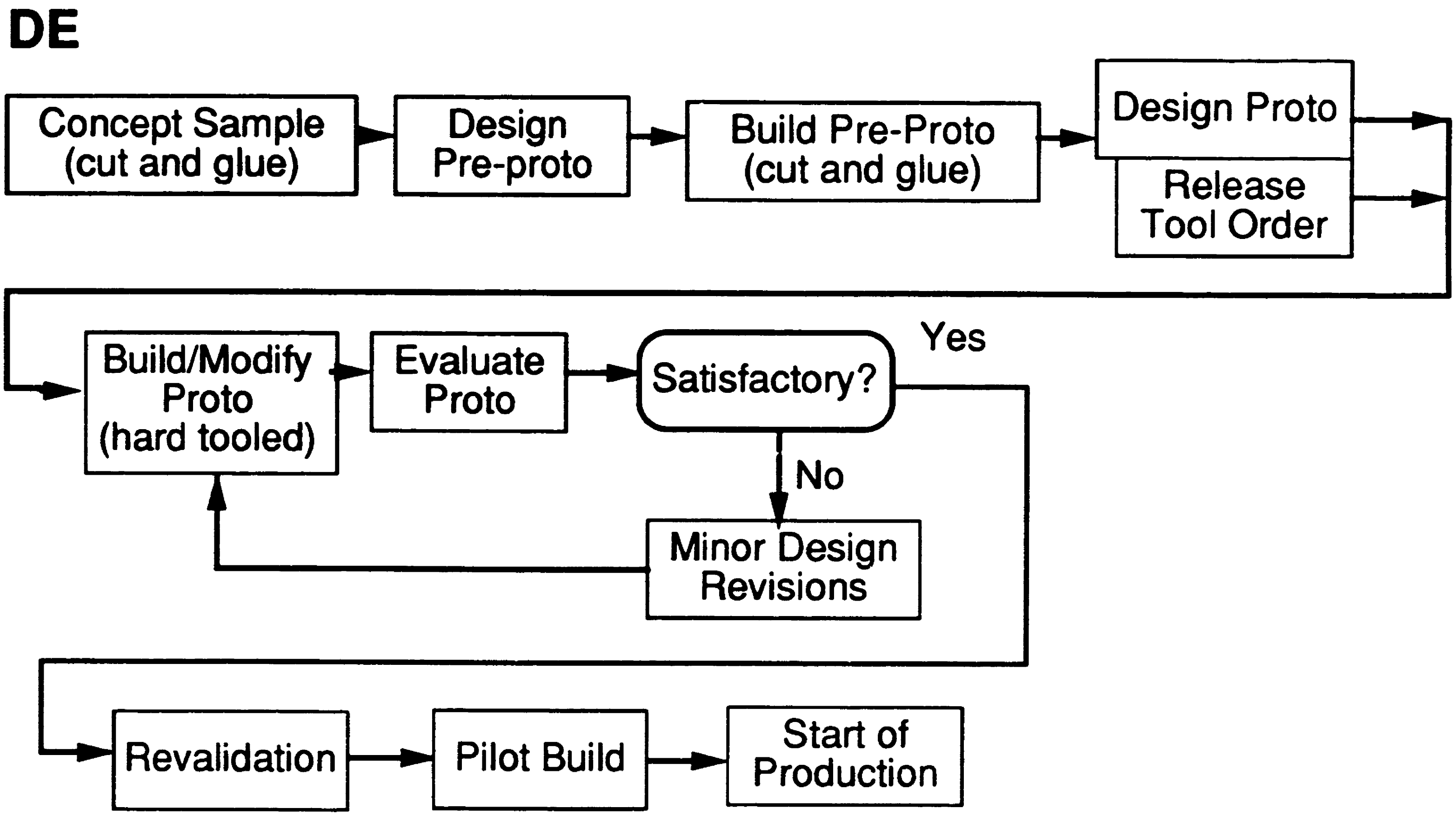
[1] For a more complete discussion of the tooling process (for metal stamping dies), see A Comparative Analysis of Best Practice in the Manufacture of Hard Dies for Automotive Stamping Operations, by Franz Drees. Masters Thesis, Mechanical Engineering and Management (Leaders for Manufacturing Program), MIT, 1991.

Figure 6.1 DE Development Sequence



directly to pre-prototypes, which are functional clusters made from hand-made, soft-metal[1] tooled or existing parts.

Once the pre-prototypes are approved, the prototypes are designed, and the hard tooling (production-intent tooling) orders are released.[2] The tooling is constructed and used to create prototype parts, from which the prototypes are built. DE mold lead time estimates vary from 20 to 36 weeks including 8 to 14 weeks of mold tryout and acceptance testing at the mold vendor and at the DE manufacturing location.[3]

These prototypes are then evaluated with a series of tests, described in Table 6.1. Validation testing typically takes 10 to 14 weeks, including time for any necessary revisions. Once the prototypes are evaluated and any necessary revisions have been accomplished, the program moves to the pilot phase, where parts are assembled using production methods and equipment. The product then goes through revalidation testing prior to the start of production.

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[1] I.e., aluminum or soft steel, in contrast to hardened tool steel.

[2] In some cases, parts with a high risk of change are tooled in soft metals. In these cases, the hard tooling is started later, after the soft-metal tooling has been tried out. The lead time for these cases is substantially longer than for the cases in which hard tool steel is used from the outset, since soft-metal tooling takes nearly as long to build as hard-metal tooling.

[3] The wide range of mold lead times suggests that the use of multiple simple parts instead of a single complex one can cut lead time in half.

Table 6.1 Typical Prototype Evaluation Tests

Lighting Evaluation
Full Functional Evaluation
High Temperature Test
Thermal Cycling (Reliability Test)
Vibration Test
Electro-magnetic Interference(EMI) and
  Radio Frequency Interference(RFI) Tests:
    - Radiated Emissions
    - Conducted Emissions
    - Radiated Susceptibility
    - Conducted Susceptibility

Electro-Static Discharge (ESD) Tests

6.3 JS Development Process

The development process for JS is similar, but differs significantly in three respects. First, prototype parts are soft-tooled.[1] Second, the performance of parts is evaluated at the earliest possible stage, and not re-evaluated at later stages of development.[2] Third, the development process is more iterative at JS than at DE, because the soft tooling used for developmental purposes has a much shorter lead time than the hard tooling used by DE.

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[1] In this thesis, the phrase "soft-tooled" refers to parts which were molded in a latex or "squeeze" mold, not parts that were molded in aluminum or soft steel molds. Since the latex molds can be made relatively easily from a master prototype part, they have a short lead time. This constitutes their primary advantage relative to metal molds.

[2] This includes a fairly comprehensive evaluation of development and prototype parts. DE, in contrast, is less likely to trust evaluations of soft-tooled parts, and more likely to re-evaluate a specific performance characteristic in a later stage of product development.

Figure 6.2 JS Development Sequence

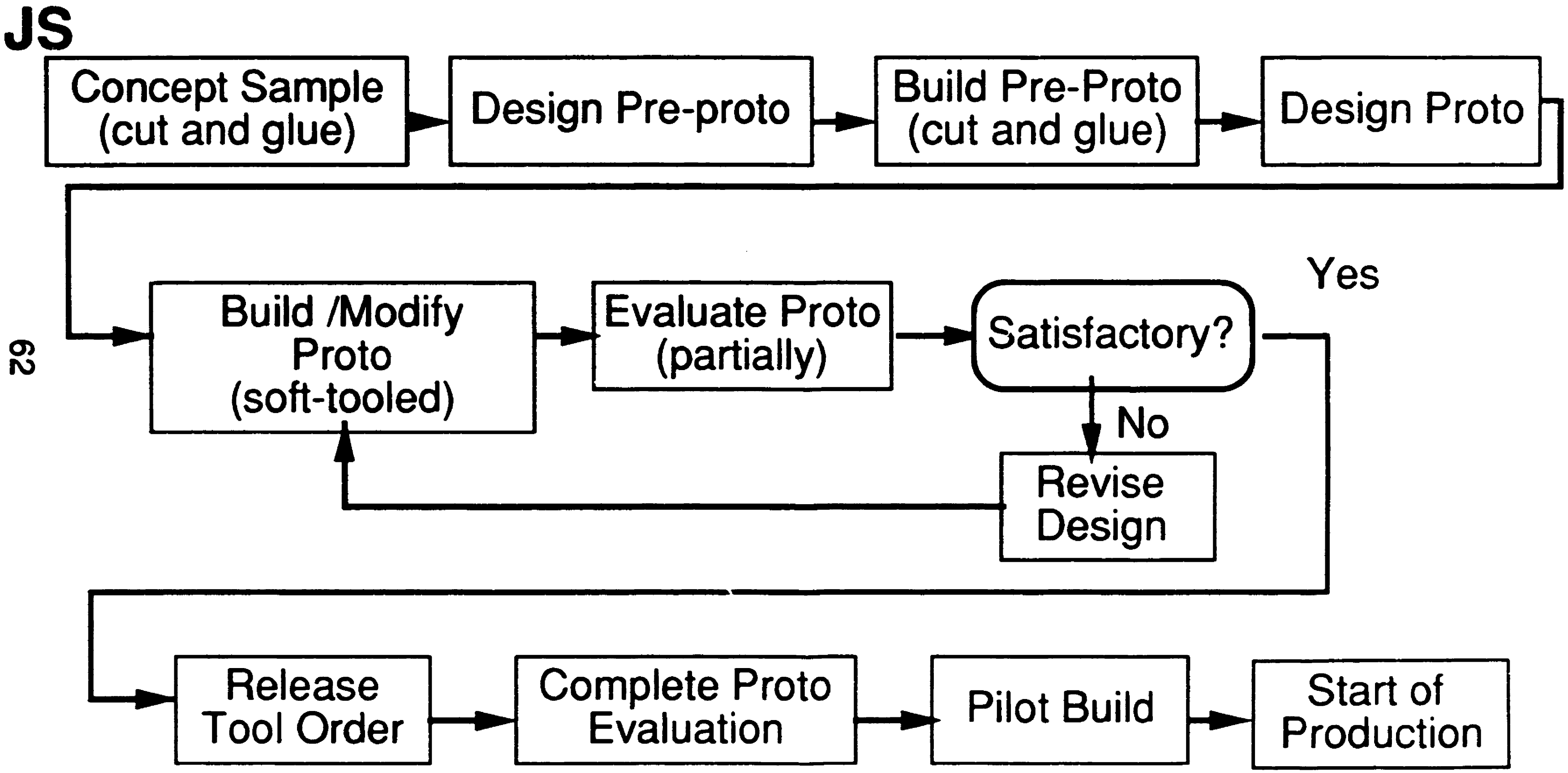

Figure 6.2 illustrates the process at JS. After the initial concept samples and functional pre-prototype parts are produced, JS produces several iterations of development prototypes. The case, lightpipes, and other plastic parts are usually squeeze-molded; the gauge and odometer mechanisms are usually standard production parts. (The pros and cons of squeeze-molded parts are discussed in a later section.)

Rather than freezing the design at an early stage as DE does, JS allows the design to continue changing through several iterations, as the design is refined, and any errors that are detected are resolved. JS performs substantial testing on the soft-tooled parts in order to detect potential problems early and fix them before hard tooling is begun. In addition to using the soft-tooled parts for lighting development, JS performs EMI and RFI testing on soft-tooled prototypes, as well as extensive temperature studies (using thermocoupled parts) to determine the heat rise at various points in the cluster. Although the soft-tooled parts cannot withstand the extreme temperatures that production parts can, the hot spots in a soft-tooled cluster are the same as those in a production cluster. Consequently, JS can use the soft-tooled prototypes and its experience to determine whether a design will perform acceptably at high temperature.

Once the evaluation of the soft-tooled part is complete, JS releases the tool order to create hard (production) tooling. This process is usually completed fairly rapidly, since the design is stable by this point and most design changes have already been incorporated. The use of simple parts (e.g. three simple lightpipes instead of one complex one) by JS also maximizes lead time reduction. In the development program observed, JS lead times were under 20 weeks from release of tools to tooling acceptance.

The completion of tooling is followed by additional testing of those aspects of the design which could not be tested using soft-tooled parts (such as high-temperature testing and reliability testing). Concurrent with this process, JS performs pilot builds, verifying that the production techniques will produce the part as expected using production tooling. The program is then ready to start saleable production.

6.4 Squeeze Molded Part Properties

The squeeze molds are usually made from masters which are in turn made of bits cut from existing parts and glued together ("cut and glue" samples). Though these squeeze-molded parts are sufficiently accurate dimensionally to evaluate (as long as the master is accurate), their material characteristics are different from production parts because they are made of a different material. The squeeze-molded parts are made of a liquid polymer which is poured into the squeeze mold and cures, rather than a plastic resin which is injection-molded at high temperature and pressure as the production parts will be. In general, the squeeze-molded parts are weaker and more brittle than production parts; they cannot withstand as high temperatures; and clear squeeze-molded parts yellow quickly, which hinders accurate assessment of the color of instrument cluster displays.[1]

6.5 Advantages of Hard Tooling Late

There are three primary advantages to delaying the start of hard tooling as JS does. First, the design is more developed. Because design engineers have more time to work on the design prior to releasing it to tooling, they can incorporate minor improvements which would have been left out if the design had been frozen earlier. Second, because the soft-tooled prototype has been evaluated, there is a higher degree of confidence in the design and consequently, a lower risk of changes to the design after tooling is started. Starting tooling later also increases the likelihood that any changes requested by the customer will be requested before tooling is started (although it also reduces the ability of the supplier to respond if a change is requested after tooling is started). Finally, the program lead time can be reduced since some testing (such as reliability testing and final high-temperature testing) can be conducted concurrent with pilot builds.[2] Since this testing can take 12-14 weeks, running these tests concurrently with pilot builds

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[1] For an evaluation of various rapid prototyping techniques, see Matthew Wall, Rough-Cut Estimating as a Strategic Prototyping Tool, Masters Thesis, Mechanical Engineering and Management (Leaders for Manufacturing Program), MIT, 1991.

[2] Strictly speaking, the decision not to run final testing parallel to pilot builds is a separate decision from the decision of whether to hard tool late or not. DE has consciously chosen not to run final testing parallel to pilot builds, although the effect of this decision on lead times may not have been fully considered.

could allow DE to perform another prototype design iteration without extending program lead times.

6.6 Disadvantages and Risks of Hard Tooling Late

Unfortunately, beginning hard tooling late also carries some risks with it. For DE, these risks fall into four major categories:

Risks of Incomplete Evaluation. Since the testing on squeeze-molded prototypes is not comprehensive, some errors cannot be detected at the soft-tooled prototype stage. For instance, soft-tooled prototypes cannot be tested for maximum temperature performance or vibration. Likewise, lighting evaluation is incomplete, since squeeze-molded lightpipes are about 80% as bright as normally molded ones. In addition, squeeze-molded lightpipes tend to yellow quickly, so they must be evaluated soon after they cure if they are to be useful. Finally, squeeze-molded snap fits do not behave the same as normally molded ones, so soft-tooled parts will not assist in their evaluation.

Risks of Undetected Changes. The risk of undetected changes depends on the method used to make the master part for the squeeze molds. If the masters are made by hand, model makers may make subtle improvements to the design, with the result that the squeeze-molded part does not match the print. Unless the model maker communicates his change to the design engineer, this type of error might not be detected until the hard-tooled parts fail to fit properly.

Risks of Inadequate Response Time. Currently, squeeze-molded parts have significant lead time in the DE model shop. Lead time can be as long as 8-12 weeks, although it is usually shorter. If the lead time for soft-tooled prototypes is not significantly shorter than for hard-tooled parts, using soft-tooled parts will not provide design engineers with additional development time. In addition, if hard tooling is begun later than normal, there will be no time to make last-minute changes to the hard tool itself.

Policy Risks. Since current corporate procedures specify that prototypes are to use production-intent designs, materials, and processes, any move toward soft-tooled prototypes on the part of DE must be justified in terms of the benefits to DE and its customers. In addition, DE must convince its customers that the risks outlined above have been guarded against. The following section describes what type of steps DE can take to mitigate the above risks.

6.7 Requirements for Using Squeeze-Molded Prototypes

If DE is to use soft-tooled prototypes in its development process, it must convince its customers that the risks outlined above have been guarded against. It can achieve this by:

- responding to any testing anomalies detected during the testing of soft-tooled prototypes, since there is no time to respond to those anomalies if they recur in hard-tooled parts as well.
- ensuring that soft-tooled parts match their prints. This requires either that DE use a prototyping method which creates the part directly from a CAD model (such as NC machining of molds), or

that any changes made by modelmakers in the construction of a hand-built master be communicated to the design engineers and designers.[1]

- developing the capability to predict hard-tooled part performance based on performance of squeeze-molded part. For some aspects of the design, such as high-temperature performance, this capability should be relatively easy to develop. For those aspects of the design which are difficult to predict, such as vibration performance, DE can use conservative designs to minimize the risk of inadequate performance for hard-tooled parts. For example, DE can use safety margins to ensure that the cluster mounting brackets will be strong enough without requiring vibration testing prior to hard tooling.

6.8 Advantages of Hard-Tooling Early

The primary advantages of hard-tooling early are that the risks detailed above are avoided. In addition, starting hard tooling early saves the expense and delay of building squeeze molds, although this expense is usually not large in comparison to the cost of hard tools. (Typical costs are under $20,000 for a squeeze mold, compared to $150,000 to $250,000 for a mold made of hard tool steel.[2]) However, if the risks detailed above are avoided, the advantages of

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[1] For an evaluation of various rapid prototyping techniques, see Matthew Wall, Rough-Cut Estimating as a Strategic Prototyping Tool, Masters Thesis, Mechanical Engineering and Management (Leaders for Manufacturing Program), MIT, 1991.

[2] The interest saved by delaying the purchase of hard tooled molds by six months may offset the cost of the squeeze molds cost, so that the net savings of hard tooling early are minimal.

beginning hard tooling late substantially outweigh the advantages of beginning hard tooling early.

6.9 Summary

Based on the above considerations, the use of soft tooling for prototype parts offers substantial savings both in cost and lead time (or added development time). Effective use of soft tooling will require development of the capability to predict hard-tooled part performance based on the evaluation of soft-tooled parts. It will also require the prompt response to any testing anomalies detected in soft-tooled parts, and strict control to ensure that soft-tooled parts properly reflect current product designs. Finally, use of soft-tooled parts will require development of customer understanding of the benefits to be derived from use of soft-tooled parts.

Chapter 7. Designed Experiment for Improved Gauges

7.1 Introduction

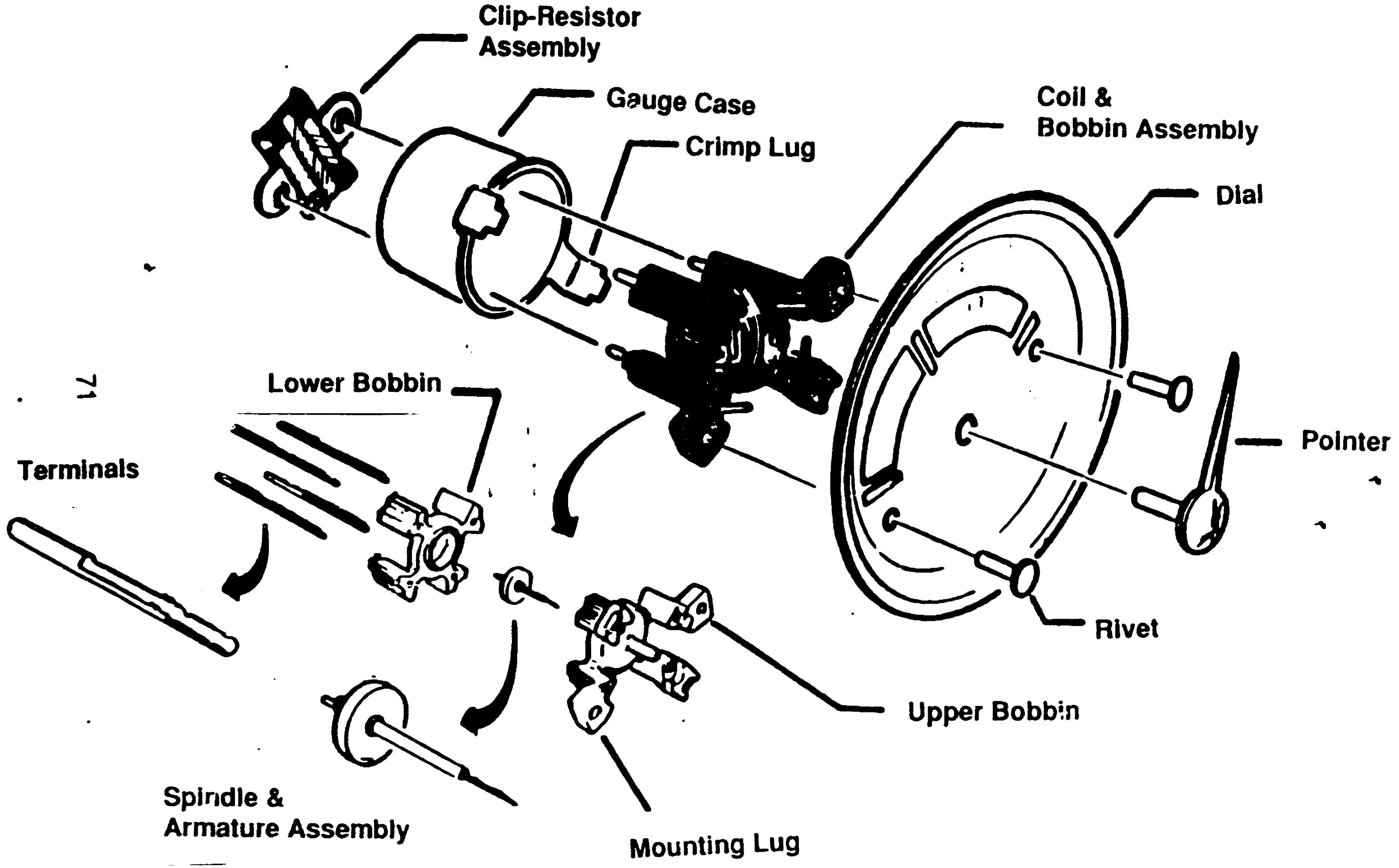
Although some of the variation in performance of air core gauges is due to variation introduced during the pointer staking process, the performance of the gauge mechanisms themselves are not completely consistent. Different gauge designs have different amounts of hysteresis, temperature sensitivity, and sensitivity to other "noise" factors. This chapter describes an experiment performed to determine the effects of various design factors on the performance of air core gauges. The intent of the experiment was to determine which combination of design choices resulted in the most robust design, that is, the design which was least sensitive to variations in manufacturing processes and gauge operating conditions. Modification of the existing gauge design in the direction indicated by the results of the experiment could result in a gauge design which performed well in a wide variety of conditions, and which performed well even when the conditions under which the gauges were manufactured were not ideal.

Section 7.2 briefly describes air core gauges; section 7.3 describes the structure of the experiment; section 7.4 describes the analysis performed; and section 7.5 describes the implications of the experiment on gauge design. Section 7.6 summarizes the results and suggests directions for further research.

7.2 Air Core Gauge Explanation

The basic Delco Electronics air core gauge mechanism is shown in Figure 7.1. Two or three copper wire coils are wound (at right angles to each other) around a two-part plastic bobbin, which contains an armature magnet on a spindle and

Figure 7.1 Air Core Gauge Mechanism



three or four terminals. The armatures are damped by means of silicone inside the bobbin. This bobbin assembly is inserted into a metal gauge case, and a calibrating resistor is attached to two of the terminals. This so-called "coil, bobbin and case assembly" (CBC) is sent to a subassembly or final assembly line, where the dial face is attached to the "ears" of the bobbin, and the gauge pointer is attached to the spindle.

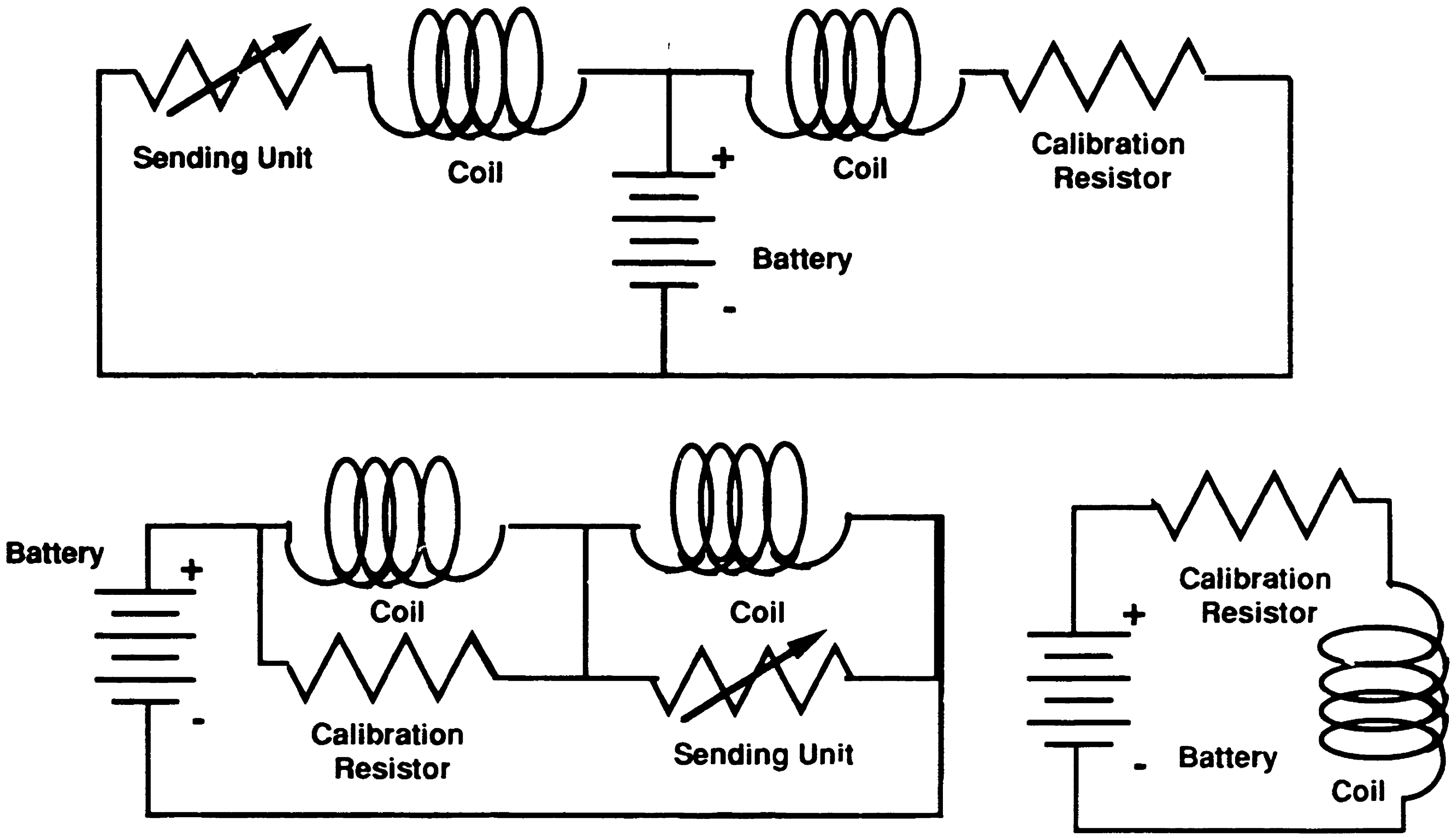
The three basic gauge schematics for auxiliary gauges are shown in Figure 7.2. Pressure and fuel gauges have a calibrating resistor in parallel with one coil, and the pressure or fuel sensor resistance in parallel with the other two coils. Temperature gauge circuits have two parts in parallel: on one half, the sensor resistance is in series with one coil, and the other coils and calibrating resistor are in series in the other half. Voltmeters have two coils in series with a calibrating resistor; they need no sensor since they measure the voltage across their terminals.

The basic principle of operation for all auxiliary gauges is the same: as the resistance of the sensing unit changes, the current flowing through the various coils changes, causing the gauge armature (and the needle attached to it) to move as the armature magnet aligns itself with the vector sum of the magnetic fields produced by the coils. For the voltmeter, a permanent magnet contributes to the vector sum, and the current through the coils varies in direct proportion to the voltage at the terminals. (See Figure 7.3).

A wide variety of parameters will determine both the performance of the gauge and its cost. First, there are requirements which are typically taken as inputs to the design process, such as the required span of the gauge, the span between specified points on the gauge (such as "Full" and "Half" on a fuel gauge), and

Figure 7.2 Air Core Gauge Circuits

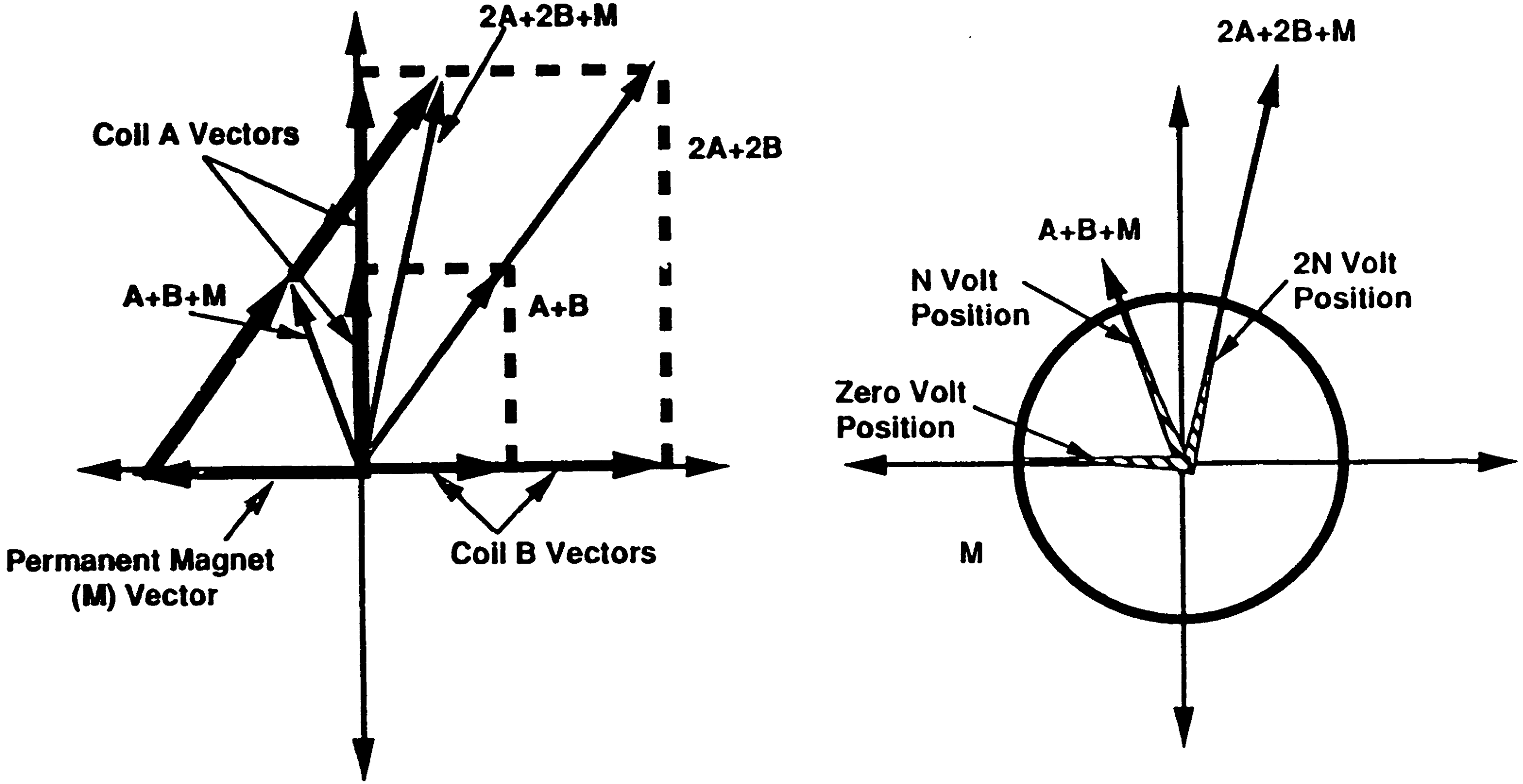
Temperature Gauge Schematic



Fuel/Oil Pressure Gauge Schematic

Voltmeter Schematic

Figure 7.3 Air Core Gauge Magnetic Field Vectors (Voltmeter)



The diagram at left depicts the magnetic fields which determine the position of a voltmeter needle. The field produced by the permanent magnet is fixed; the fields produced by the A and B coils are proportional to the current through them. The resultant field is the vector sum of the three component fields. The voltmeter armature magnet, to which the needle is attached, aligns itself with the resultant field. The figure at right shows the needle position at zero volts, N volts, and 2N volts. Other air core gauges operate on the same principle.

the sending unit curve (e.g. the relationship between the number of gallons of gas in the fuel tank and the resistance of the fuel sending unit). In addition, there are cost, accuracy, and reliability targets (within a specified operating environment) for the gauge. Finally, there are design parameters which, while not specified explicitly, will determine whether the gauge meets its targets. These parameters include wire size, coil and calibrating resistor resistances, case material (which affects hysteresis and therefore accuracy), and magnet material, strength, and geometry, among others. These design parameters affect not only the ideal performance of the gauge, but also its sensitivity to so-called noise factors. Noise factors include both variation introduced during the production process, such as variations in material properties of raw materials, magnet charge, magnet position, and winding tension of the coils, as well as variations in conditions of use, such as ambient temperature or humidity, the presence of external fields, and so on.

7.3 Experimental Design

The design parameters which were investigated in this designed experiment are noted in Table 7.1 below. For an existing air core gauge, six factors were selected, and a designed experiment was conducted using these factors and three manufacturing noise factors. (See Table 7.2 for a description of the basic design.) The gauges thus created were then tested at three different input conditions (high, medium and low) and at three different temperatures (-40°C, 25°C, and 90°C), and the angular position of the gauges from a reference point was measured. The medium input condition was measured from both directions (i.e. rising and falling) in order to obtain an estimate of hysteresis.

Table 7.1 Factors Investigated in Designed Experiment

Design Factors	Number of Levels
Magnet Shape	2
Number of Magnets	2
Case Material	2
Current	3
Coil Strength	2
Magnet Supplier	2

Noise Factors	Number of Levels
Wire Lot	2
Magnet Position I	2
Magnet Position II	2

7.4 Results and Analysis

For each of the 24 basic designs, there were four gauges that were measured at three input conditions. These 12 measurements were made at each of three temperatures; the raw measurements are included in the appendix. The variance of the 12 measurements was then calculated for each input condition (high, medium, or low), and the variance was regressed against the various design factors to determine the relationship of the design factors to gauge variance. The results are summarized in Table 7.3. The best model fit was found using the variance of the "high" input setting, possibly due to the reduced hysteresis at that setting.

The initial raw data analysis showed a very poor fit due to the presence of an outlier (Series 2, Number 11). Since the gauges had already been dismantled when the outlier was detected, a "dummy" data point (essentially, data from

Table 7.2 Basic Experimental Design

Factor/	#1	#2	#3	#4	#5		N#1
Design	**A**	**B**	**C**	**D = AB**	**E = AC**	**F = BC**	**G = ABC**
1	0	0	0	0	0	0	0
2	1	0	0	1	1	0	1
3	0	1	0	1	0	1	1
4	1	1	0	0	1	1	0
5	0	0	1	0	1	1	1
6	1	0	1	1	0	1	0
7	0	1	1	1	1	0	0
8	1	1	1	0	0	0	1
	Sub-Design		**#6**	**N#2**	**N#3**		
		1	-1	0	0		
		2	0	0	0		
		3	1	0	0		
		4	-1	1	0		
		5	0	1	0		
		6	1	1	0		
		7	-1	0	1		
		8	0	0	1		
		9	1	0	1		
		10	-1	1	1		
		11	0	1	1		
		12	1	1	1		

Table 7..2 Basic Experimental Design. The first five design factors and one noise factor were incorporated into an eight-run saturated fractional factorial design. These eight basic designs were then fully crossed with one three-level design factor and two two-level noise factors to create 96 gauges. Each of the 24 designs had 4 replications, which differed only in the level chosen for the two noise variables.

Table 7.3 Regression Results

The top half of the table below shows the regression of the various design factors against the variance of the gauge position in the "High" input setting. The lower half shows the contribution of each factor to the total sum of squares.

```
Dependent variable is:      LV5V
R□ = 64.7%      R□(adjusted) = 60.9%
s = 0.2376  with  72 - 8 = 64  degrees of freedom

Source       Sum of Squares    df    Mean Square    F-ratio
Regression   6.62948            7        0.94707     16.8
Residual     3.61419           64       0.056472

Variable     Coefficient    s.e. of Coeff    t-ratio
Constant     2.21387        0.0699             31.7
A            -0.558407      0.0560             -9.97
B            -0.045558      0.0560             -0.813
C            0.007942       0.0560              0.142
D=AB         -0.027471      0.0560             -0.490
E=AC         -0.191087      0.0560             -3.41
F            -0.078045      0.0343             -2.28
Temp(C)      0.000272       0.0005              0.516
```

```
Analysis of Variance For      LV5V

Source    df    Sum of Squares     Mean Square     F-ratio    Prob
A         1      5.61274           5.61274         102.43     0.0000
B         1      0.037359          0.037359          0.68179  0.4121
C         1      0.001135          0.001135          0.02072  0.8860
D=A       1      0.013584          0.013584          0.24790  0.6203
E=A       1      0.657258          0.657258         11.995    0.0010
F         2      0.374277          0.187138          3.4152   0.0392
T()       2      0.149959          0.074979          1.3683   0.2621
Error     62     3.39736           0.054796
Total     71    10.2437
```

Series 2, Number 10) was substituted for the spurious data in 2-11. As a result of this substitution, the R^2 value of the regression model rose from 35% to over 60%.

The regression shows that three factors (A, E, and F) appear to have a significant effect on gauge variability, while the remaining factors do little to explain the variation in gauge variability.

As a result of the very large shifts in gauge position due to process noise, the linear model was not a very accurate representation of the physical forces at work in the (round) gauge to fit the data well. Future experiments should use smaller variations in noise factors to ensure that the model fits better.

7.5 Implications for Gauge Design

The above results suggest that designs in which the design factors A, E, and F, are set at the levels A=1, E=1, and F=1 will have less variability in gauge performance than other designs. However, this result only underscores the tradeoffs inherent in gauge design, since in each case, changing the design from the current design, in which A=0, E=0, and F=0, will adversely affect either the cost of the gauge, its operating temperature (and therefore its reliability), or both. DE managers must decide if the gains in gauge performance justify the added expense.

7.6 Summary and Recommendations for Further Research

This chapter described a designed experiment which examined the effect of various design parameters on gauge variability. Three factors were found to have an effect on gauge variability, but in each case, reducing variability increased the cost of the gauge. Future work is necessary to establish the value of reduced variability in air core gauges. Such work could use concepts such as Taguchi's Quality Loss Function to estimate the cost of poor quality for gauges. In addition, future work could develop a non-linear model which more closely represents the physical forces at work in the gauge. Such a model would enable engineers to better understand the effects of various design parameters on gauge performance, and consequently design better gauges.

Chapter 8 Conclusion

8.1 Introduction

The past seven chapters have examined the development and operations practices of Delco Electronics and a Japanese Supplier from several angles. This chapter summarizes the results of the thesis, and suggests directions for further research.

8.2 Summary of Results

In examining the practices of DE and JS in the areas of process capability, product/process standardization, and development processes, five major lessons emerge, namely:

- **the value of process capability.** DE could realize savings of over $12 million per year by improving process capability in applique processing and pointer staking.
- **the value of product and process standardization.** Standardization of products and processes could reduce process engineering expenses, enable greater re-use of capital equipment and enhance the process capability of existing processes by allowing engineers to focus on a few well-understood processes
- **the importance of organizational learning.** Effective organizational learning disseminates best practices broadly within an organization, raising the overall performance level of the organization.
- **the importance of adequate development prior to hard tooling.** By performing more extensive testing prior to beginning hard tooling, DE

can reduce the number and extent of late changes to tooling, allowing lead times to be shortened without compromising product quality.

- **the importance of design philosophy.** By matching manufacturing capabilities with customer needs, an effective design philosophy channels product designs into configurations which the manufacturing organization can produce effectively. The result, for JS and potentially for DE, is enhanced process capability, and consequently designs that consistently meet the customer's needs at a competitive price.

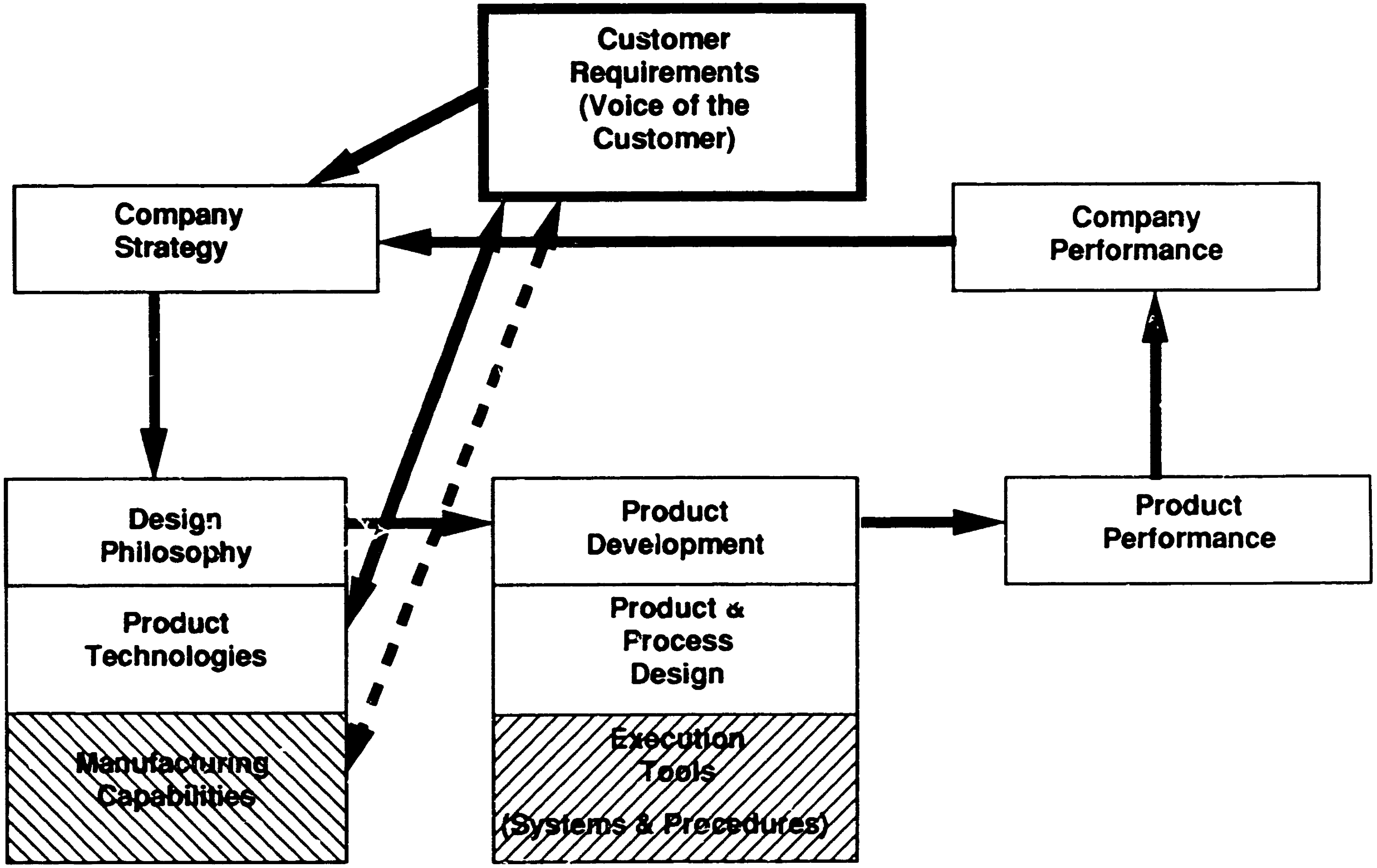
Figure 8.1 diagrams the relationship of design philosophy to customer requirements and product development. An effective design philosophy both meets customer requirements and takes into account existing manufacturing capabilities. In doing so, design philosophy can enhance the competitive position of automotive manufacturers, enabling them to develop superior products at a competitive price.

8.3 Opportunities for Further Research

Though this thesis has examined several aspects of engineering and operations practices at Delco Electronics, there are several areas touched upon in this thesis which could be investigated further in future research. Below are five potential topics.

1. **Air Core Gage Process Capability.** Over 10% of the scrap (by value) generated at DE-Flint is generated in one department -- the Air Core Gage assembly line. This project would involve looking at sources of scrap within this department and identifying ways to reduce or eliminate this scrap. Issues to be considered could include product cost, product quality, process capability at several points in

Figure 8.1 Design Philosophy



the assembly process, tradeoffs between up-front testing costs and costs of undetected failures, and objectives (such as backward compatibility (i.e. compatibility of proposed design changes with existing designs) of any proposed design changes.

2. **Success Factors/Operational Issues for Robotic Processes.** Both DE and its competitors have investigated the use of flexible automation for various processes, such as driving screws and inserting bulbs, with varying degrees of success. This project would seek to identify the key success factors for robotic projects. The project could be oriented toward analysis of past projects and might include development work on current projects. Alternatively, the project could focus on current robotic processes and potential improvements to their performance in terms of uptime, quality, or performance.

3. **Process Capability in Applique Screening.** The process used to produce appliques at DE is good, but could be even better. Due to the high cost of appliques, improvement in the process capability of the silk screening process used for appliques could lead to substantial savings for DE. This project could include both analysis of opportunities and implementation of some improvements to the current process.

4. **Product Modularity.** DFA (Design for Assembly) dogma emphasizes the importance of modular design. Since instrument clusters are built using both modular and non-modular designs, this product represents an ideal opportunity to examine the costs and

benefits of each type of design. Issues to be examined could include tooling costs, development time, ability to use common parts and processes, design constraints, quality issues, and assembly costs. The project could address not only which product approach is more expensive, but <u>why</u>, and examine the implications of these reasons for future process (or product) development.

5. **Product/Process Standardization.** This project would examine the current state of DE product and process standardization and identity opportunities for further standardization. Analysis could include examination of the tradeoffs involved in standardization, especially if standardizing means using a high-cost process or component.

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Chapter 5

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Appendix A. Raw Experimental Data

The first two columns of the table show the series(1) and number within a series(1,2, or 3) for the data. The numbers within a series have been grouped to enable the calculation of a variance. For example, in series 1, the data for gauges 1, 4, 7, and 10 was combined to create the data shown below as data for Series 1, Number 1. In the same way, gauges 2,5,8, and 11 were grouped, as were gauges 3, 6, 9, and 12. These gauges all had the same levels for design factors; they differed only in the settings of the noise factors. Columns C through H show the levels of the indicated design factors, column I shows the average hysteresis, and columns J through M show the average readings at the low, medium, and high input conditions. Columns N through S show the variance of the same readings.

	A	B	C	D	E	F	G	H	I	J	K	L
2	Series No.		A	B	C	D=AB	E=AC	F	Temp(C)	AVHYST	AVLCW	AVMED
3	1	1	0	0	0	0	0	-1	-40	3.85	34.73	52.37
4	1	1	0	0	0	0	0	-1	25	3.56	40.05	65.96
5	1	1	0	0	0	0	0	-1	90	6.13	39.01	57.46
6	1	2	0	0	0	0	0	0	-40	3.37	41.25	61.64
7	1	2	0	0	0	0	0	0	25	3.02	35.03	52.91
8	1	2	0	0	0	0	0	0	90	5.06	39.36	57.57
9	1	3	0	0	0	0	0	1	-40	2.14	45.54	68.88
10	1	3	0	0	0	0	0	1	25	4.64	40.16	62.08
11	1	3	0	0	0	0	0	1	90	6.02	40.17	61.6
12	2	1	1	0	0	1	1	-1	-40	1.15	67.25	92.62
13	2	1	1	0	0	1	1	-1	25	1.16	66.56	92.34
14	2	1	1	0	0	1	1	-1	90	1.34	73.9	96.97
15	2	2	1	0	0	1	1	0	-40	0.86	66.3	91.03
16	2	2	1	0	0	1	1	0	25	1.05	64.98	89.85
17	2	2	1	0	0	1	1	0	90	1.3	69.79	92.86
18	2	3	1	0	0	1	1	1	-40	0.45	83.91	104.76
19	2	3	1	0	0	1	1	1	25	0.85	71.94	95.79
20	2	3	1	0	0	1	1	1	90	1	73.82	96.31
21	3	1	0	1	0	1	0	-1	-40	5.05	51.78	71.36
22	3	1	0	1	0	1	0	-1	25	3.69	43.14	59.61
23	3	1	0	1	0	1	0	-1	90	4.92	48.68	66.56
24	3	2	0	1	0	1	0	0	-40	3.16	72.32	94.59
25	3	2	0	1	0	1	0	0	25	3.99	57.83	79.74
26	3	2	0	1	0	1	0	0	90	6.01	55.13	75.29
27	3	3	0	1	0	1	0	1	-40	2.37	72.34	94.1
28	3	3	0	1	0	1	0	1	25	4.99	43.81	61.24
29	3	3	0	1	0	1	0	1	90	6.42	44.63	63.31
30	4	1	1	1	0	0	1	-1	-40	1.51	84.3	105.66
31	4	1	1	1	0	0	1	-1	25	2.07	82.64	104.66
32	4	1	1	1	0	0	1	-1	90	1.74	90.8	109.72
33	4	2	1	1	0	0	1	0	-40	1.47	80.87	101.11
34	4	2	1	1	0	0	1	0	25	1.88	75.49	97.89
35	4	2	1	1	0	0	1	0	90	1.74	79.8	100.82
36	4	3	1	1	0	0	1	1	-40	0.81	91.42	109.82
37	4	3	1	1	0	0	1	1	25	1.5	79.38	103.48
38	4	3	1	1	0	0	1	1	90	1.43	80.31	103.5
39	5	1	0	0	1	0	1	-1	-40	2.21	35.64	57.25
40	5	1	0	0	1	0	1	-1	25	5.28	40.93	59.17
41	5	1	0	0	1	0	1	-1	90	2.74	48.57	73.79
42	5	2	0	0	1	0	1	0	-40	2.95	31.41	50.34
43	5	2	0	0	1	0	1	0	25	3.59	36.33	56.04
44	5	2	0	0	1	0	1	0	90	2.12	39.58	62.79
45	5	3	0	0	1	0	1	1	-40	2.02	37.48	60.69
46	5	3	0	0	1	0	1	1	25	5.22	39.17	63.8
47	5	3	0	0	1	0	1	1	90	5.7	38.23	64.04
48	6	1	1	0	1	1	0	-1	-40	4.03	52.02	73.68
49	6	1	1	0	1	1	0	-1	25	3.84	58	80.54
50	6	1	1	0	1	1	0	-1	90	3.66	66.92	88.66
51	6	2	1	0	1	1	0	0	-40	2.89	55.67	79.02
52	6	2	1	0	1	1	0	0	25	2.8	57.66	81.29
53	6	2	1	0	1	1	0	0	90	3.08	63.74	86.55
54	6	3	1	0	1	1	0	1	-40	1.64	58.57	81.06
55	6	3	1	0	1	1	0	1	25	2.1	55.35	78.34
56	6	3	1	0	1	1	0	1	90	2.42	59.98	82.49
57	7	1	0	1	1	1	1	-1	-40	5.76	44.02	61.99
58	7	1	0	1	1	1	1	-1	25	5.28	48.8	67.71

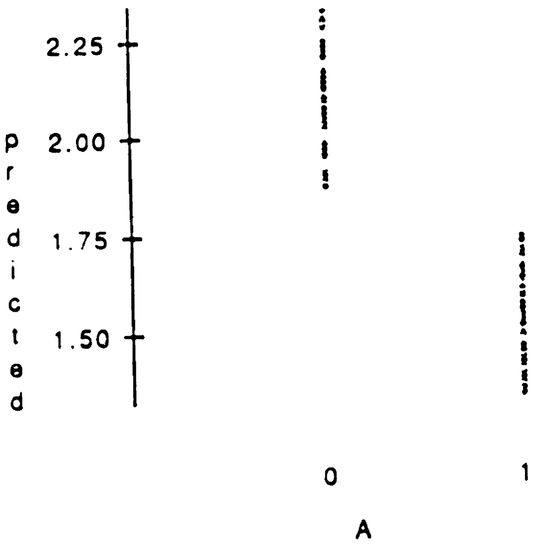
	A	B	C	D	E	F	G	H	I	J	K	L
2	Series	No.	A	B	C	D=AB	E=AC	F	Temp(C)	AVHYST	AVLOW	AVMED
59	7	1	0	1	1	1	1	-1	90	3.88	62.16	85.18
60	7	2	0	1	1	1	1	0	-40	4.34	42.03	61.04
61	7	2	0	1	1	1	1	0	25	3.54	45.47	64.77
62	7	2	0	1	1	1	1	0	90	5.06	40.02	58.57
63	7	3	0	1	1	1	1	1	-40	1.63	70.8	90.46
64	7	3	0	1	1	1	1	1	25	4.04	53.93	71.52
65	7	3	0	1	1	1	1	1	90	4.82	58.2	74.97
66	8	1	1	1	1	0	0	-1	-40	4.1	77.44	99.18
67	8	1	1	1	1	0	0	-1	25	3.53	82.14	103.4
68	8	1	1	1	1	0	0	-1	90	3.4[illegible]	94.18	110.03
69	8	2	1	1	1	0	0	0	-40	2.62	83.85	103.16
70	8	2	1	1	1	0	0	0	25	2.45	83.61	103.35
71	8	2	1	1	1	0	0	0	90	2.66	92.2	108.44
72	8	3	1	1	1	0	0	1	-40	1.79	84.73	102.05
73	8	3	1	1	1	0	0	1	25	2.52	80.89	99.74
74	8	3	1	1	1	0	0	1	90	2.36	86.8	103.48

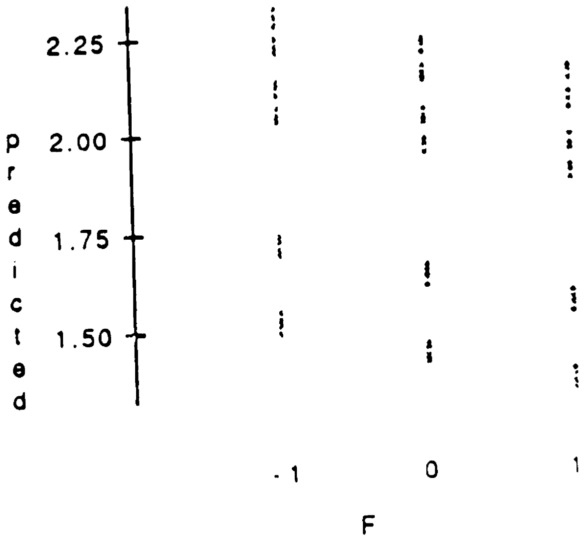
	M	N	O	P	Q	R	S
2	AVHIGH	AVSPAN	VARHYST	VARLOW	VARMED	VARHIGH	VARSPAN
3	74.76	40.03	2.99	44.73	141.24	211.97	82.14
4	86.99	46.95	3.47	83.14	303.93	383.25	123.62
5	79.09	40.09	6.73	68	146.56	187.55	67.02
6	83.94	42.69	5.17	111.22	275.21	283.45	47.51
7	76.25	41.21	3.09	20.33	81.47	150.87	62.44
8	79.45	40.1	11.83	108.52	274.61	301.54	53.03
9	93.09	47.55	1.16	110.13	156.89	82.06	15.91
10	86.12	45.96	8.64	78.17	184.17	170.64	30.81
11	85.88	45.71	16.36	66	186.68	167.5	28.95
12	108.5	41.26	0.02	49.26	29.58	14.74	11.27
13	107.94	41.39	0.1	55.76	37.75	21	10.87
14	111.22	37.32	0.1	47.15	28.55	15.08	10.47
15	108.01	41.21	0.1	88.87	59.9	26.3	19.72
16	106.95	41.97	0.11	108.58	80.74	40.6	18.72
17	109.08	39.29	0.13	104.38	76.38	34.72	18.99
18	118.9	35.09	0.04	67.85	37.42	19.22	15.33
19	112.1	40.17	0.08	50.82	43.97	24	5.01
20	112.4	38.58	0.23	67.07	55.9	33.2	5.92
21	91.73	39.95	1.27	75.17	146.87	131.34	14.62
22	79.31	36.18	2.88	235.75	423.38	371.29	26.45
23	87.69	39.02	0.29	115.8	220.04	192.01	23.8
24	110.44	38.12	0.72	102.22	147.89	121.16	6.02
25	99.01	41.18	2.39	62.98	126.3	156.42	24.16
26	95.88	40.75	0.14	67.13	112.51	149.84	24.52
27	110.7	38.35	0.81	26.91	36.42	22.9	6.2
28	82.86	39.06	7.25	62.73	99.65	121.21	20.13
29	85.23	40.6	2.52	24.14	52.75	60.72	22.54
30	118.38	34.08	0.34	119.98	50.94	29.45	38.44
31	117.32	34.67	0.47	111.4	51.67	28.4	34.03
32	121.46	30.66	0.17	91.46	41.94	26.84	29.21
33	115.4	34.53	0.49	168.51	101.43	44.17	40.74
34	112.73	37.24	0.43	130.43	95.13	45.06	22.3
35	115.06	35.27	0.4	131.49	79.96	35.3	30.61
36	121.2	29.78	0.23	102.88	33.57	20.35	38.56
37	116.73	37.35	0.09	209.68	57.68	25	95.34
38	116.74	36.43	0.13	222.61	66.01	31.36	93.23
39	80.64	45	0.15	23.74	149.18	187.34	81.21
40	82.51	41.58	7.87	127.99	246.37	192.25	44.65
41	95.95	47.39	0.11	73.6	90.18	63.46	11.95
42	75.21	43.81	4.71	39.07	201.04	227.49	78.86
43	84.12	47.79	1.32	35.28	58.72	24.94	7.95
44	87.43	47.85	1.28	152.52	371.83	220.51	24.75
45	92.26	54.79	2.29	43.37	121.94	36.35	23.5
46	91.25	52.09	17.04	73.65	213.08	83.39	0.64
47	94.99	56.76	16.6	40.2	147.31	52.78	16.61
48	93.25	41.24	0.24	67.55	122.65	89.24	3.47
49	98.71	40.71	0.29	122.12	145.71	69.5	8.47
50	105.53	38.61	0.16	128.75	95	36.88	27.97
51	97.58	41.91	0.27	42.03	54.14	33.55	1.75
52	99.14	41.49	0.16	69.36	72.34	38.56	5.05
53	103.13	39.39	0.5	54.01	44.06	19.87	9.15
54	99.91	41.34	0.12	88.96	114.05	74.91	1.74
55	96.79	41.44	0.01	78.25	108.17	73.81	1.24
56	100.55	40.57	0.02	107.88	131.2	89.74	2.34
57	84.43	40.42	1.18	61.16	150.35	177.62	31.33
58	89.38	40.58	4.43	99.79	165.17	139.88	12.7

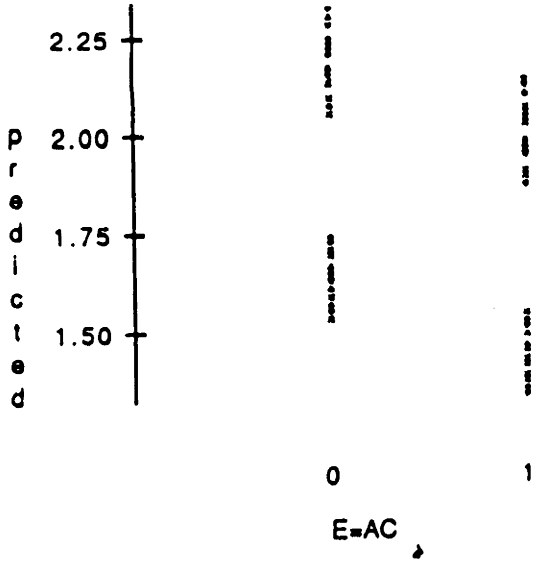
	M	N	O	P	Q	R	S
2	AVHIGH	AVSPAN	VARHYST	VARLOW	VARMED	VARHIGH	VARSPAN
59	103.95	41.8	3.24	183.48	256.15	128.22	8.7
60	85.57	43.54	1.42	29.47	104.51	110.88	26.44
61	87.37	41.89	4.2	129.7	218.12	209.29	30.9
62	82.45	42.43	0.79	25.41	92.3	129.5	40.33
63	105.67	34.88	1.58	264.23	89.66	27.14	156.71
64	90.32	36.4	4.32	429.05	315.2	135.57	130.22
65	94.56	36.36	12.1	327.79	240.9	84.73	116.89
66	113.01	35.57	2.93	187.72	75.71	31.78	69.06
67	115.03	32.89	1.01	186.77	65.74	35.32	66.08
68	120.24	26.06	0.63	115.96	54.03	30.61	28.99
69	115.58	31.73	0.41	131.11	64.48	38.24	32.73
70	115.35	31.73	0.07	148.05	65.94	40.61	36.65
71	119.4	27.2	0.32	105.82	55.42	32.38	25.57
72	114.65	29.93	0.67	100.91	78.21	37.08	16.49
73	112.26	31.38	0.57	100.11	81.9	47.8	12.47
74	115.35	28.55	0.27	100.76	66.75	36.79	16.35

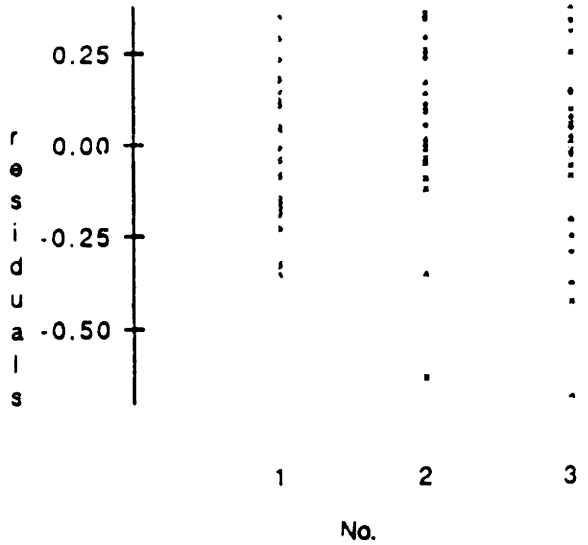
Appendix B. Regression Plots

The plots below show the predicted values for each level of factors A, E, and F; the plots on the next page show the residuals for the gauges by series (1-8) and by number within series (1-3).





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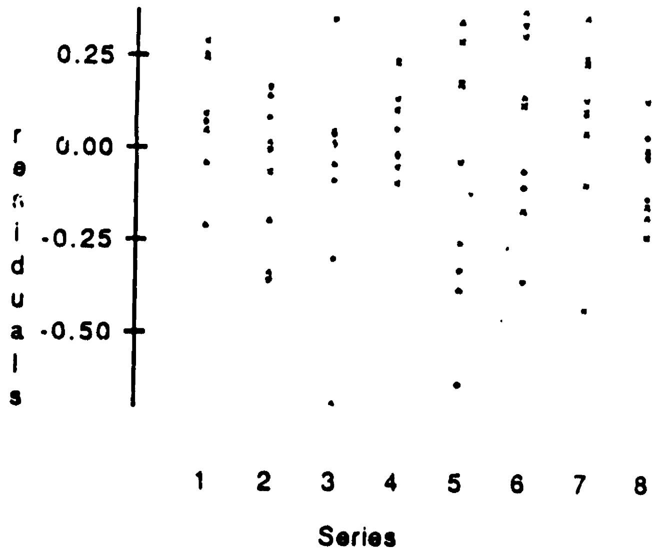
0.00
-0.25
-0.50
residuals
1
2
3
No.


0.25
0.00
-0.25
-0.50
residuals
1
2
3
4
5
6
7
8
Series