A Method for Systems Design Using Precedence
Relationships: An Application to Automotive Brake Systems

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ABSTRACT

A tool called the Design Structure Matrix, developed by Steward [1981], is applied to the design of an automotive brake system. The methodology is used to order and organize the design activities for the brake system design process on the basis of the information flows involved. Because it discriminates between decisions which may be made independently and decisions which constitute a "simultaneous subsystem", the methodology is useful for both engineering and organizational aspects of design.

Once simultaneous subsystems have been identified, a system can be decoupled by "tearing" or guessing a sufficient number of parameters to iterate through the design once. Multiple iterations may still be needed for final solution. In the case examined, 103 parameters were ordered in a design structure matrix and a simultaneous subsystem of 34 parameters was found to exist. This system could be solved by tearing 12 of the 34 parameters.

Several methods for solving simultaneous subsystems defined by the design structure matrix are presented as alternatives to the tearing procedure. These include axiomatic design, designed experiments, fuzzy set theory, shunt diagrams (developed by Steward [1981]), and other weighted function methodologies using a priori knowledge and input/output relationships.

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1.0 Introduction/Motivation

This paper addresses the task of designing complex mechanical systems. The difficulties in designing such systems do not arise simply from their engineering complexity, but also from the organizational complexity necessary to manage the system design process. A methodology for the design of complex mechanical systems is applied which addresses both the engineering and the organizational factors to shorten design cycle time and improve the design itself. The implications of this methodology are analyzed and improvements for systems design are proposed.

1.1 Brake System As An Example

This research was conducted at an automotive brake system component supplier, and that setting is used to explore the complex relationships and design dependencies in systems design, and discuss the systems design methodology. The automotive brake system affects vehicle motion by controlling the resistance to wheel rotation. Also, it provides the interface between the wheel and suspension; and between the steering and final drive. A typical brake system has front disk brakes and rear drum brakes.

The brake system contains about 28 principal components [see Black, 1990]. Among these are the pedal, master cylinder, control valves, disc brake assembly, drum brake assembly, and parking brake. A power booster (or just booster) is often added to increase the power input to the master cylinder. Within the brake assembly exist such components as the caliper, rotor, pads & lining, and steering knuckle for disk brakes; and the wheel cylinder, shoe & lining, drum, and drum backing plate for drum brakes.

See Appendix A for illustrations of various brake system components.

1.2 Problem Setting/Description

Engineering Issues

This work focuses on interdependencies among the individual components in the brake system. Design of systems is primarily a process of discovering, analyzing, and resolving tradeoffs, and very often involves the simultaneous determination of several variables. Brake design involves such a process of tradeoffs among design parameters. As an example, consider the design of a brake system for higher torque which can be accomplished by using a larger diameter rotor, a smaller master cylinder, larger wheel cylinders, a larger booster, or a higher pedal mechanical advantage.

Efficient and effective brake system development requires that designers be informed of parameter changes and their ramifications throughout the system. At the brake component supplier we worked with, very little systems thinking is undertaken by the individual component designers. It is commonly (but usually incorrectly) accepted that the best individual component will make the best brake system. In fact, the company uses a process similar to the "envelope approach" referred to by Robertson [1990]: designers at all levels wait for the proper envelope space constraints to be handed down from a previous level of design with little consideration and understanding of "the big picture".

In comparison, a systems approach structures the process so that component interactions can be understood easily. Such a systems approach analyzes interfaces and

specifications in terms of the effects on an entire system. As will be discussed, the design structure matrix (DSM) shows when the envelope approach is sufficient and when a systems approach would be more useful. The DSM helps to make this distinction through the identification of "blocks" (interdependent design decisions).

Organizational Issues in Design

Organizational management challenges arise from the complexity of managing and coordinating the systems design task. A complex system typically requires a significant number of designers. At the brake supplier we studied, design activities are difficult to coordinate due to geographical dispersion of the forty designers (among four separate locations), and the component complexities discussed above. For any particular brake system, responsibilities for the components typically reside in and shift among different locations over the design life cycle.

As evidence of the coordination difficulties, we found that several designers with prime responsibilities in different areas (and located in separate plants) would claim responsibility concerning a particular brake system parameter. In addition, they sometimes disagreed over the information necessary to determine that particular parameter. This occurred with about 20% of the original 103 brake system parameters we identified.

Clark et al (1987) found evidence that product development projects in the auto industry have shorter overall lead times and require fewer total engineering resources when organized with a "heavyweight" project manager, as opposed to a functional

organization. As our research project commenced, brake system development at this company was changing from a functional structure to a heavyweight subsystem manager structure. That is, a "heavyweight" manager is now responsible for all brake system development, but each development project does not have its own project manager. Rather, the subsystem manager serves as the project manager for each individual project.

The most widely used tool (and conceptual model) available to such project managers is that of PERT/CPM (Project Evaluation Review Technique / Critical Path Method). (See, for example, Wiest and Levy (1969).) However, for the brake system design challenges at the company we worked with, this tool has two shortcomings. The first of these, addressed by the methodology of this paper, is that many individual activities in product development projects are temporally interdependent so that, for example, in a group of activities, each contains the others as precedent activities. That is, rather than activity A strictly preceding or following activity B, for example, A and B are interrelated activities that must be performed simultaneously (typically by iteration). PERT/CPM models do not allow for such relationships.

The second shortcoming of PERT/CPM for use by the brake system product development manager is that it cannot analyze the capacity and scheduling problems that arise when more than one brake system are simultaneously in the processing network. In particular, if several brake systems are simultaneously being designed, then they may compete for and queue up for certain engineering resources. For such a case, activity time estimates must include queueing time, which is typically nontrivial to calculate. Although such analysis is beyond the scope of this paper, Harrison (1990) has pointed

out that the model of Nguyen (1990) might be used to help analyze this problem. See also Varma (1990).

This rest of this paper proceeds as follows. Section 2 discusses related literature, section 3 describes our methodology, section 4 presents our analysis and results, section 5 contains a discussion of some additional issues, section 6 discusses a few ideas for further research, and section 7 contains concluding discussion.

2.0 Related Literature

Much literature exists on approaches to design for manufacturing. Nevins and Whitney et al [1988] discuss methodologies for concurrent product and process design. They also give a broad framework for systems design and apply various rules to improve the design's ability to be both manufactured and assembled.

Suh [1990] postulates two axioms which underlie all design processes. The first axiom relates to the independence of functional requirements in an optimal design. The second axiom depends on axiom 1 and allows a designer to choose a design with minimum information content between functionally uncoupled designs. Suh uses the axioms to develop a design framework. With this framework, designers can systematically create more efficient designs.

Suh [1990] and Stoll [1986] develop some rules for the design process which take manufacturing considerations into account. These rules may be adapted or included in the design structure matrix described below (for fuller treatment, see Black [1990]).

Clausing and Hauser [1988] survey and consolidate a large volume of literature to

discuss a methodology deploying the customer's voice into design specifications using a tool called the House of Quality. Clausing [1989] also develops a framework for deploying the customer's voice through the four phases of quality function deployment (House of Quality, Parts Deployment, Process Deployment, Product Deployment). (The design structure matrix used here can act as an intermediate stage between the House of Quality and Parts Deployment: the outputs of the House of Quality, design requirements, can act as some of the inputs to the design structure matrix. The outputs of the design structure matrix, refined design requirements, can act as the inputs to Parts Deployment. Parts Deployment then relates accurate design requirements and part characteristics in a relationship matrix similar to the House of Quality.)

The literature above focuses on design but is not oriented towards systems management. On the other hand, there is a significant amount of "systems" literature that explains how to identify the existence of a system. Checkland [1981] has written one of the seminal works on systems thinking and has helped to create a systems movement. In particular, Checkland defined "a systems approach" and made a detailed explanation of systems thinking. Ackoff [1981] has given sound definitions and concepts to systems terms as well as provided an organizational model for systems thinking. Churchman [1971] developed some early concepts applying systems thinking to design of components and their interrelationships to accomplish goal seeking behavior. Jones [1982] develops some guidelines for defining systems boundaries and while Blandford [1985] lays out helpful methodologies, processes, and tools for understanding complex design problems. Nadler [1985] gives clear examples, definitions, and connections between systems

methodology and the design process. Rouse [1987], Nadler [1970] and Sage [1977][1987] all apply behavioral concepts to the difficulties involved in systems design. More mathematically based systems literature provides dynamic mathematical modeling approaches (Miser [1985], Shearer et al. [1967], Augusto et al. [1980]) and bond graphing (energy transferring) techniques for simple systems (Paynter [1961]).

Related to practices in product development management, Clark (1989) and Clark et al (1987, 1989a, 1989b) have collected and analyzed a wealth of data from automobile manufacturers on three continents. They find evidence for significantly superior performance by Japanese auto manufacturers, attributable, in part, to better project management, better supplier strategy and use of suppliers, and better problem solving methods.

3.0 The Design Structure Matrix (DSM) and Automotive Brake Systems Design

To analyze the brake system design problem, we have applied a method developed by Steward [1981] which organizes design parameters at the conceptualization stage of design. The method stresses implementation of systems concepts and understanding of system complexity from a system manager's viewpoint. In particular, we apply a tool called the Design Structure Matrix (DSM) which utilizes information flow in the design process to say what must be performed at a particular stage in design (but not how it should be performed). (See also Eppinger and Whitney [1989].)

3.1 Terminology

We use the following terms in the remainder of the paper:

Simultaneous Subsystem - a set of design tasks where the information parameters for each task are simultaneously dependent on all other tasks' information parameters within the same simultaneous subsystem.

System - a set of design tasks where the structure of information flows have the characteristic that simultaneous subsystems can be shown to exist.

Block - used in conjunction with the DSM, a term denoting a simultaneous subsystem; they are called "blocks" because they appear as square matrices along the diagonal of the DSM [Steward, 1981].

Principal Circuit - a circular dependency of information flows [Steward, 1981]. Alternate terminology would be a "loop".

Tear - the act of "guessing" a precedence relationship; tearing corresponds to removing a mark (defined next) from the DSM or related blocks; it results in the relative ordering of parameters within a block [Steward, 1981].

Mark - an "X" placed in the DSM to denote that a precedence relationship exists between two information parameters; marks can also be of numerical form to denote the desirability of tearing order (or existence of a-priori knowledge) [Steward, 1981].

Complete Feedback Tear Set - A group of tears which will produce a lower triangular DSM, that is, one with no blocks. These are all the relationships which must be "guessed" to begin the design process [Steward, 1981].

3.2 Data Collection

Information Flow and the Brake System Design Process

Prior to our study, no one at the firm had tried to systematically catalog and organize the entire brake system design process using precedent information flows. To do this, we began by interviewing 40 key component designers for the brake system and identified 100 decision points for critical design parameters in a complete brake system. (See Black [1990] for complete description of parameters.) The designers' own words were used in the creation of the design parameter definitions.

A two-step process was used to solicit data from designers. First, the 100 parameters and the interview data were used to determine the precedence relationships among the parameters. Determining precedence relationships for each parameter took the form of determining the information needed to make or begin any particular decision. For example, before determining the booster envelope/attachment points, one must know the available room under the hood, the temperature ranges under the hood, and the master cylinder envelope & attachment points.

In the second step, 23 of the designers were approached with the first pass precedent relationships and were asked to reflect on their earlier inputs in light of the whole picture provided by the precedence matrix. The data was sorted so that, for example, the master cylinder designer could view the list and see the parameters which fall under his/her direct control:

Parameter	Precedent Parameters
Master Cylinder Envelope & Attachment Points	● Available Room Under Hood
Master Cylinder Bore Size -	● Vehicle Weights (Mass, Diameter & Length Center of Gravity) ● Master Cylinder Envelope & Attachment Points ● Wheel Torque Required at 4 Wheels ● Caliper & Drum Pistons' Displacement vs Line Pressure curves

(The precedent activities list for the master cylinder bore size has been simplified slightly for this example.) Each designer reviewed "his parameters" on the list and corrected any mistakes.

After a comprehensive review of the data by the designers, several important observations were made:

1.) Of the original 100 activities, about 20 were deleted and 23 were added.

2.) Frequently, more than one designer considered a particular parameter to be in his domain. In such cases, when two designers considered the precedent information necessary to make or begin to make a decision on an activity, they often chose different precedent information (with some overlap).

3.) Designers had a tendency to ask for too much precedent information unless the goals were repeatedly stated as "finding that precedent information for each activity to allow one to make or begin the decision." Of course, all designers would like to know everything completely before giving an answer, but some measure of risk is necessary in order to make the problem manageable. Separating "need to know" from "nice to know" data required judgement calls on

a number of occasions. Some researchers are working on systematic ways of addressing this issue (Eppinger and Whitney [1989]).

4.0 Analysis And Results

4.1 Analysis

The Design Precedence Matrix

The revised set of activities and precedent information was entered into a square matrix termed the "Design Precedence Matrix" [Steward, 1981]. This matrix replaces a network diagram and provides a compact representation of the precedence information and relationships provided by the designers.

Creation of the design precedence matrix is straightforward. A simple example using 13 of the actual parameters and their relationships will be used for illustrative purposes (see figure 1). (See Black [1990] for the full 103-parameter design precedence matrix.)

The Design <u>Precedence</u> Matrix

		1	2	3	4	5	6	7	8	9	10	11	12	13
1	CUSTOMER REQUMNTS	⊗												
2	WHEEL TORQUE		⊗		X									
3	PEDAL MECH. ADVANT.	X		⊗	X	X			X		X			X
4	SYSTEM LEVEL PARAM'S	X			⊗									
5	ROTOR DIAMETER	X	X	X	X	⊗		X	X		X	X		X
6	ABS MODULATOR DISPL.						⊗			X				
7	LININC COEFF. - FRT.			X	X	X		⊗	X		X			X
8	PISTON - REAR SIZE		X		X				⊗		X			
9	CALIPER COMPLIANCE			X	X					⊗	X			X
10	PISTON - FRONT SIZE		X		X				X		⊗			
11	LINING COEFF - REAR			X	X	X			X		X	⊗		X
12	BOOSTER - MAX STROKE												⊗	X
13	BOOSTER REACT. RATIO		X	X	X	X		X	X		X	X		⊗

Figure 1

Noting that the matrix uses columns to represent "From" and rows to represent "To", consider activity [3], pedal mechanical advantage. To determine the required ratio of force input to force output of the pedal's lever action, the designer must know [1] the customer requirements (such as the maximum allowable input force), [4] system level parameters (such as vehicle weights), [5] the rotor diameter (which has a large effect on output wheel torque), the piston sizes ([8] & [10]) (which strongly influence output torque), and [13] the booster reaction ratio (which also amplifies an input force from the pedal for additional mechanical advantage). In reality, a few other parameters are also required, such as the master cylinder piston size, but were left out of the example due to size limitations.

The Design Structure Matrix (DSM)

The design structure matrix (Figure 2) is an ordered listing (given design dependencies) of the design decision process. To get from the design precedence matrix to the DSM, an algorithm called partitioning must be performed on the design precedence matrix. The partitioning heuristic (first described in Steward [1981] and later revisited by other researchers) seeks to place each parameter in the DSM in the temporal order in which it can be determined.

Not only does partitioning order (and renumber) the design parameters, but most importantly, it points out where circuits (simultaneous subsystems) exist. In effect, two types of regions exist within the DSM. Those areas where design is either a sequential or parallel process and those areas where design is simultaneous.

The DSM aids in the development of a complete systems approach. The matrix clearly reveals the design decision process, which can aid the development of a consistent plan even for the most complex systems. As mentioned earlier, by tracing across the rows of the matrix, one can see what information must be known before making any decision. By tracing down the columns of the matrix, one can see how changing a parameter will affect other parameters in the future. The "ripple" effects from parameter changes can be traced down and across until all concerned are notified and made aware of the changes. This matrix shows the information flow in the design process and it shows who must communicate with whom, and when.
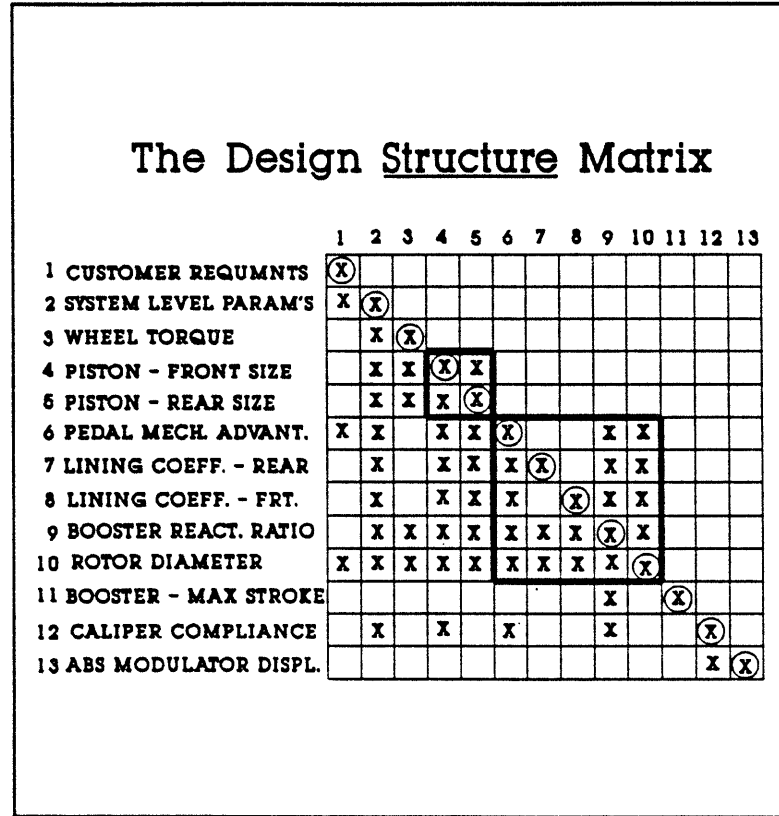
The Design Structure Matrix

	1	2	3	4	5	6	7	8	9	10	11	12	13
1 CUSTOMER REQUMNTS	(X)												
2 SYSTEM LEVEL PARAM'S	X	(X)											
3 WHEEL TORQUE		X	(X)										
4 PISTON - FRONT SIZE		X	X	(X)	X								
5 PISTON - REAR SIZE		X	X	X	(X)								
6 PEDAL MECH. ADVANT.	X	X		X	X	(X)		X	X				
7 LINING COEFF. - REAR		X		X	X	X	(X)		X	X			
8 LINING COEFF. - FRT.		X		X	X	X		(X)	X	X			
9 BOOSTER REACT. RATIO		X	X	X	X	X	X	X	(X)	X			
10 ROTOR DIAMETER	X	X	X	X	X	X	X	X	X	(X)			
11 BOOSTER - MAX STROKE									X		(X)		
12 CALIPER COMPLIANCE		X		X		X			X			(X)	
13 ABS MODULATOR DISPL.												X	(X)

Figure 2

The blocks within the DSM indicate where a purely sequential approach to design is not sufficient. In order to better understand these blocks, we will examine two examples which are shown in figures 2 and 4. These blocks are actually subsets of the 34 X 34 block in appendix B. In figure 2 we will be concerned about the block of parameters 6-10 which relates to the stopping torque that the brake system can develop. The block of figure 4 concerns some aspects of the heat dissipation capabilities of the brake system.

First, we can understand the information represented by the block of figure 2 by tracing it through one line at a time. To begin determining the pedal mechanical advantage [6], the designer must know the booster reaction ratio [9] and the rotor

diameter [10]. The rear lining coefficient of friction [7] requires knowledge of the pedal mechanical advantage [6], booster reaction ratio [9], and the rotor diameter [10]. The front lining coefficient of friction [8] requires knowledge of the pedal mechanical advantage [6], the booster reaction ratio [9], and the rotor diameter [10]. To determine the booster reaction ratio [9] requires knowledge of the pedal mechanical advantage [6], the rear lining coefficient of friction [7], the front lining coefficient of friction [8], and the rotor diameter [10]. Determining the rotor diameter [10] requires knowledge of the pedal mechanical advantage [6], the rear lining coefficient of friction [7], the front lining coefficient of friction [8], and the booster reaction ratio [9].

The same information can also be represented as a node graph shown in figure 3 and helps to explain the term "system complexity".
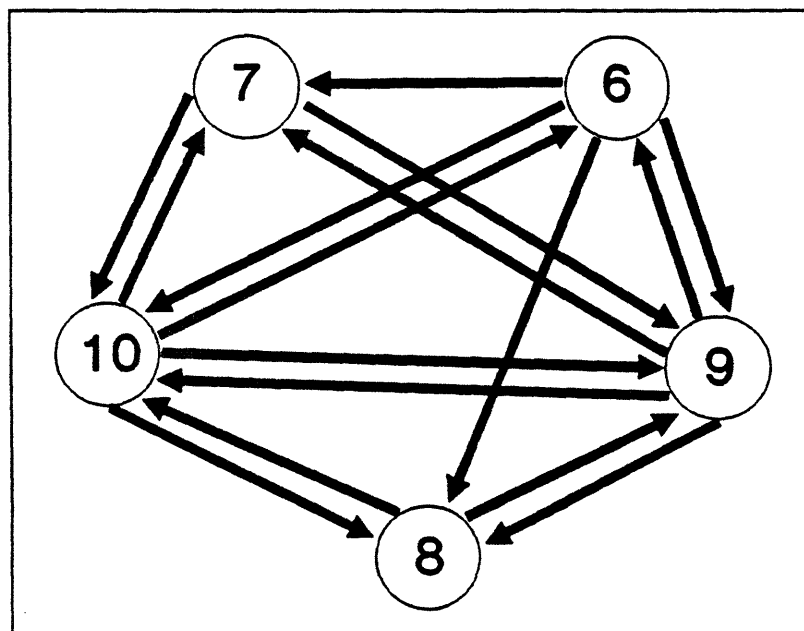
Figure 3

While such a representation is possible for a small number of parameters, it becomes
unwieldy for large numbers of parameters. The parameters in the block of figure 2 and
in the node graph of figure 3 are in fact quite interrelated as they all have a strong effect
on the wheel output torque. This relationship can be written in a general form as
follows:

$$f(MA, BRR, MCA, PA, \mu, RD, torque) = 0 \qquad (1)$$

Such a general form can always be used to interrelate the quantities in a block.
However, sometimes we have sufficient information to quantify this relationship. In this
case, we can write an explicit relationship between torque and the parameters as follows:

$$Torque = constant \times MA \times BRR \times MCA^{-1} \times PA \times \mu \times RD \qquad (2)$$

Where

MA   = Pedal Mechanical Advantage
BRR   = Booster Reaction Ratio
MCA^{-1} = Master Cylinder Area
PA   = Piston Areas
μ = Lining Coefficient of Friction
RD   = Rotor Diameter

When such a quantifiable relationship is available, it can be used to help reduce
the complexity of the block and therefore to simplify the design process (see section 6.3
of this paper). The information contained in figure 4 shows five parameters relating to

the brake system's ability to dissipate power.

	46	47	48	49	50
46. SPLASH SHIELD GEOM.	⊗	X			X
47. ABS SENSOR LOCATION	X	⊗			
48. AIR FLOW UNDER CAR	X		⊗		X
49. WHEEL MAT'L (ALUM?)				⊗	X
50. WHEEL DESIGN			X		⊗

Figure 4

Here, we can see that the splash shield geometry, which protects the bearing from road dirt, depends on the ABS sensor location as well as the wheel design. By protecting the bearing from dirt, the splash shield can also inhibit cooling airflow. The wheel design, which can be anything from spokes to a solid hub, will affect airflow into the brakes.

The ABS sensor, which senses a rotating ferrous disk on the bearing, must be placed so that its delicate components will not sustain heat damage and must be fitted with the splash shield. Air flow depends on the splash shield (inside) and wheel design (outside). The wheel material depends on the wheel design (other factors such as torques have been left off this example). Wheel design depends, among other things, on the air flows. Note that inadequate airflow can lead to both short lining life and less effective brakes (lining coefficient of friction gets smaller as the pads get hotter).

In the case of figure 4, no quantitative relationship is readily available, and we can only use a general form such as that of equation (1) to interrelate the parameters.

Partitioning and Blocks - Simultaneous Subsystems

The design structure matrix permits easy identification of "blocks", which represent simultaneous subsystems. Blocks are defined such that 1.) within each block, there is a path from any node to any node, and 2.) only a one-directional path can exist between a node in one block and a node in another block. The partitioning process does not provide an ordering of parameters within a block. A procedure called "tearing" (discussed below) orders the parameters within the block.

Blocks represent the essence of system complexity. Note that within the DSM of figure 2, a block is shown in thick black lines from parameters [6] through [10]. An important question now arises: "If all the parameters in a block are simultaneously dependent, which ones and how many must be guessed before design iterations can begin and a feasible design can be identified?" This question leads to principal circuit analysis and tearing.

Finding Design Iteration Cycles - Principal Circuits

To trace out the loops of a block, chose a mark (X) in a row, then read up to the column number. Go to the same row number as this column and read across to another mark. Read up to the column, etc. Continue this procedure until the first mark is encountered again. This process defines a starting parameter and traces out succeeding

precedent parameters until encountering the initial parameter again. In this way, a circuit can be defined. Figure 5 shows a principal circuit for the large example DSM block of figure 2:
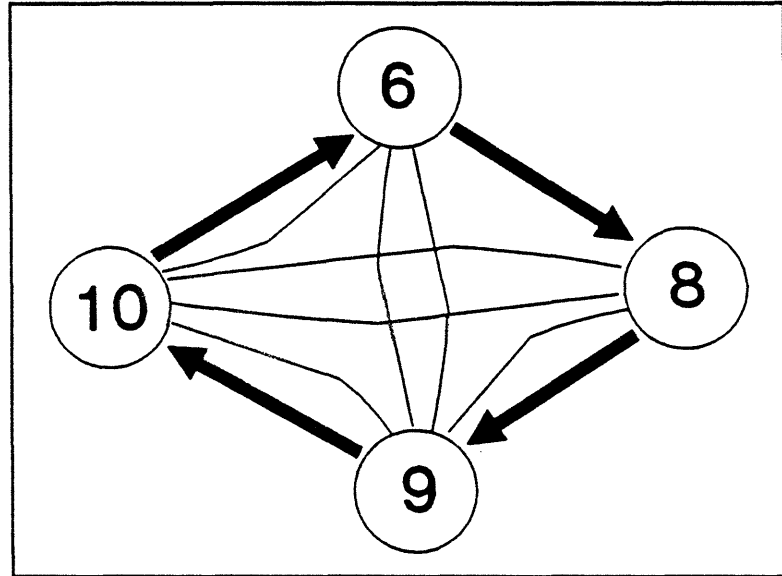

Figure 5

To illustrate the degree of complexity that can arise, we include in Appendix B the largest (34 X 34) block from the full (103 X 103) study [Black (1990)]. A principal circuit for the appendix B example is shown in figure 6.
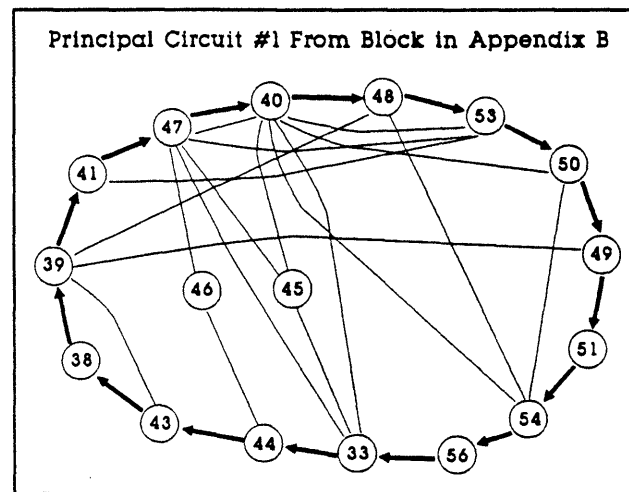
Figure 6

Tearing - Guessing for least influence

With reference to the DSM, the act of "tearing a mark" refers to guessing a value or relationship to remove this dependency. That is, if A depends on B and B depends on A, "tearing" is the act of removing one of these dependencies. One might "tear" the arc from B to A so that only a one-way dependency remains (that from A to B). In this example, if the arc from B to A is "torn", then the value of B that is needed to determine A is a guessed value. This value of B is the initial guess which will start the design iteration process.

Tearing embodies substitution and iteration, which are accepted methods of solution in a complex, coupled design process. After finding the initial data and dependencies, the designer must sort out the least costly approaches for solution. The goal is to obtain a block ordering that allows the design process to focus on "good" design parameters quickly and accurately. Tearing is the process of obtaining a set of initial values to begin the subsystem design process.

Re-ordering the Block after Tearing

When does tearing end? Phrased differently, when does the system designer know that he or she has torn (or guessed) enough values to begin the design management and iteration process?

After each tear (or set of tears), the block must be re-partitioned. After repartitioning, a new set of marks will now appear above the diagonal and a new set of tears must be made. While making more guesses than necessary is costly in terms of time or quality, several marks can be torn in the beginning of the process at each iteration until the block becomes lower triangular, at which point "enough" tears have been made to begin executing the design process.

4.2 Results For the Brake System Design Example

Interview-based knowledge of the brake system design process was used to select a set of initial tears (or guesses) to make the block lower triangular. In other words, the most easily determinable values were torn first and the matrix was repartitioned to check for lower triangularity.

In the short example of figure 2, we might begin by developing educated guesses for the rotor diameter [10] and booster reaction ratio [9]. Numbers [9] and [10] may be chosen, for example, because their tears will immediately result in a lower triangular block. Remember that the block can be reordered in any way to leave specific parameters above the diagonal. Tearing these relationships makes the block lower triangular and thus creates a complete feedback tear set.

For the 34 X 34 block of appendix B, one possible set of parameters which make up a complete feedback tear set are:

36.) Drum Material

40.) Splash Shield Geometry - Front

46.) Splash Shield Geometry - Rear

50.) Wheel Design

51.) Tire Type/Material

55.) Lining - RR. Vol & Area

56.) Rotor Width

58.) Dash Deflection

61.) Pedal Mechanical Advantage

62.) Lining - Front Vol & Swept Area

64.) Booster Reaction Ratio

65.) Rotor Diameter

These 12 parameters are involved in 40 relationships within the block. In effect, 40 marks were torn to create this solution. After 12 cycles of tearing and repartitioning, the block was reordered to become lower triangular (see Black [1990] for new order). Based on the discussions and interviews we had with designers and managers, these parameters were the least uncertain.

Starting with initial values for the above 12 parameters, the brake system design process encompassing the complex 34 X 34 subsystem may now begin. Ramifications for

managing this process are discussed below.

It should be noted that when a tear is made, it is usually in the context of removing one dependency in a relationship. In solving the 34 X 34 block, all the marks in a parameter's column were torn at once. Imagine two separate relationships (say 1 and 2) dependent on the value of one parameter "Z". Relationship 1 requires complete knowledge of "Z", while relationship 2 requires a less exact description of "Z" to begin the iteration process. This approach assumed "Z" was well enough defined for all relationships in the block to be torn from all at once. Clearly, this is an approach of convenience rather than rigor. It assumes a "real world" scenario of one designer determining the most realistic values for his or her parameter and then letting all other designers use these values. A better approach would be to make tears and repartition one at a time to gauge the effects of each tear. For example, tearing one "expensive" relationship (one we know little about) may greatly reduce the number of feedback arcs above the diagonal; whereas tearing four well known "cheap" relationships might only reduce the number of feedback arcs by four. This points out that some parameters are involved in many circuits. Research on determining the level of a priori knowledge for individual tears is ongoing (Eppinger and Whitney [1989]).

Systematic Partition and Iteration

Performing the partitioning procedure by hand led to a 34 by 34 block (Appendix B) containing 68 marks below the diagonal. These 68 were the result of the partitioning procedure and were not placed below the diagonal on purpose. However, using software

developed by Rogers and Padula at the NASA Langley Research Center in Virginia, the feedbacks in the 34 X 34 brake system block were reduced from 68 (by hand) to 40 (with software) (see Rogers [1989]).

We chose a complete feedback tear set based on a priori knowledge of which guesses we could easily make. We now ask, "How many iterations will this block take before we determine the exact values?" In essence, the final set of values which will solve the block is a fixed point vector in the parameter space (Todd [1976]). Designers and managers must now make estimates of the number of iterations necessary to find the fixed point vector.

Making the initial 40 tears (equivalently guessing at 12 parameters) led to a reordering for the 34 X 34 block of appendix B. This block is now lower triangular and design may proceed in an orderly manner from the top of the block to the bottom.

Principal circuits were found from the block. Upon examination of the dependencies, initial guesses were made to completely "break" the loops. We may now begin the iterations. This requires estimates from designers/managers as to the length of time and number of iterations required to solve the parameters in the loop.

PERT and CPM have been acceptable methods for managing large-scale projects since the 1940's. These methods can now be applied to the design process. Once the number of iterations for a particular circuit have been defined, these loops may be unwrapped and placed in a PERT/CPM diagram similar to figure 7.
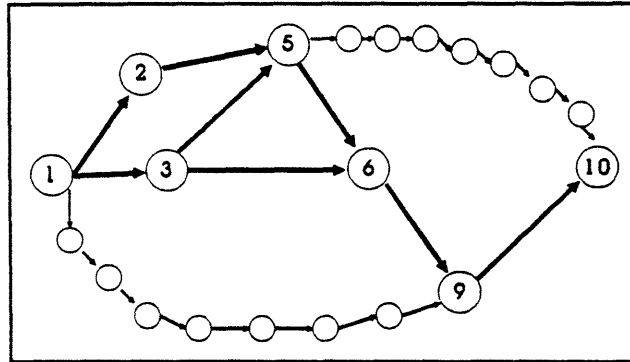
Figure 7

The marks above the diagonal in the DSM show where we make assumptions to start the design iteration process. Design reviews occur after the last task in the block is completed to test whether the starting assumptions are valid or whether another iteration is required.

The DSM has given us an order for the brake system design process. It has also shown the inherent complexity in systems design by pointing out the existence of simultaneous subsystems (blocks). Using the blocks, designers may now examine the parameter decisions necessary to organize and start the design iteration process.

Organizationally, the DSM and block(s) have created order from the complex design process by diagramming the information flows in the brake system design process. The timing of design reviews can now coincide with the completion of block activities and the reviews can specifically concentrate on the "above diagonal" assumptions which were used to start the iteration process. Although most designers would have had a sense that many things were dependent, few would have suspected the parameters to be so intertwined. Now all designers, engineers, and managers will be working according to the same plan.

Managing the Design Process

The Design Structure Matrix is a tool for the heavyweight project manager. In the case of the brake system supplier we studied, it serves as a road map for organizing the design work. In addition, it guides the rationalization of allocating design tasks to the four design locations. In particular, tasks that all reside in one block should be all assigned to the same location. The brake system development manager who sponsored our work is adopting the DSM to manage the development of all new brake systems in his company.

5.0 Additional Issues

5.1 Data Collection Issues

What can or did go wrong with the data collection process? Input was solicited from a group of about 20 designers. Sometimes the designers claimed overlapping responsibilities for a particular parameter or did not agree on the precedent activities of that parameter. Metrics should be established on the level of detail required for the precedence relationships. For all parameters, the designers might be asked, "For this particular parameter, please name all the information which is necessary to determine or to begin to determine this parameter." Designers in teams would be able to reach a common understanding of such a metric and be able to determine parameter responsibilities.

5.2 Parameter Definition

In most cases, the parameters to be determined could not readily be quantified with a single number. This complexity makes numerical solution with substitution or designed experiment approaches more difficult. The parameters we used were chosen based on the designer's own words to effect buy-in to the methodology. A further round of the methodology might focus on more accurate numerical explanations for the given parameters.

More specifically, one purpose of this exercise was to use the physical structure and constraints of the brake system to generate implications for the organizational structure of the brake system design group. To draw out such results, further work must be done (both for generic systems and for the system described here) on parameter (and constraint) definition and organizational implications.

5.3 Cost as a Coupling Effect

The DSM lumps all cost issues into the customer requirements. The matrix does not consider cost interactions and tradeoffs during parameter determination. However, it is obvious that cost can be related in some way to every parameter. Similarly, Suh [1990] notes that cost is best kept as a constraint and not a design parameter during conceptual design.

As parameters approach their cost limits, designs will become coupled. Parameter decisions and ultimately designs should be evaluated against cost constraints upon completion of critical design loops. It is possible that cost targets can be

formulated as parameters and placed directly into the DSM.

6.0 Suggestions for Further Research

6.1 Using A Priori Knowledge to Make Tears

Steward [1981] and Eppinger & Whitney [1989] discuss the use of a priori knowledge in making tears. The concept itself is straightforward: associated with every mark in the matrix is a level of confidence in the pre-existing knowledge of that parameter. Instead of using X's to fill in the matrix, these authors suggest using a scale of 0 to 9. A "0" mark indicates a more easily torn value while a higher value indicates a parameter which is more difficult to tear. Given the links in a principal circuit and a priori knowledge for each link, it should be a relatively simple task to define the least costly set of tears.

6.2 Axiomatic Design

As this paper suggests, a system implies an inherently coupled design. The block structure of the DSM describes a physically coupled design. Suh's [1990] axiomatic design approach seeks to uncouple such designs by defining independent relationships among functional requirements (FR's) at a given level in the design hierarchy. An intriguing research topic could be developed exploring the axiomatic design implications for a complex design such as the brake system.

6.3 Designed Experiment Approach

The DSM defines relationships among parameters and shows where subsystems exist, thus reducing the set of parameters which require experimentation. Designers can also narrow the range of "interesting" parameters based on past experience.

Given a small set of parameters defined through the use of the DSM or experience, the relationships among the parameters may be accurately modeled by first or second order polynomial relationships. A set of such relationships would define a system of simultaneous equations, the solution being the desired design.

In a case where the relationships within the block could be developed either analytically from first principles or from experience, the number of tears that need to be made could be substantially reduced (or eliminated entirely). An example is the explicit relationship of equation 2 and its application to the block of figure 2. However, often these relationships are not known and must be determined experimentally. Here, methods of statistical design of experiments can be used to define polynomial relationships between independently varied parameters and measured outputs. Examples of such methods are the Taguchi orthogonal array and response surface methods (see Taguchi [1985], Box and Draper [1969]). Designed experiments could be used to define relationships between some or all of the parameters in a DSM, thus reducing or eliminating the number of tears needed to solve the design.

6.4 Fuzzy Sets and Designer Contract Language

The theory of fuzzy sets has an application in the context of the system design

problem (Schmucker [1984]). Because the early stages of design involve decision making in uncertain environments, Zadeh [1975] argues that these restrictions play an important role in the human ability to conceptualize the problem, form concepts, and recognize patterns. Later, Zadeh postulates that fuzzy set theory is most appropriate for problems which are too complex or ill-defined to be susceptible to analysis by conventional techniques.

This can apply to our design problem if designers, whether component or system level, can specify ranges and plausibility of acceptable values early in the design process. As designers feed each other more accurate information, the sequential processes of design will disappear giving way to parallel design of all interrelated parameters. For fuller treatment, see Black [1990].

6.5 Design Drivers

A design driver is a parameter that, once determined, significantly aids the decoupling of numerous other parameters. Use of the DSM could be enhanced significantly by research to discover, with minimal computation, whether good design drivers exist for a given problem and to identify them. One possible method for accomplishing this is to create a coefficient of output/input for each design activity. For example, each design activity acts as the input to X other activities (read across the rows in the DSM) and the output to Y other activities (read down the columns of the DSM). A coefficient representing output/input or Y/X may show, relatively, how much a particular activity is used by and uses other activities. Low "coefficients" would mean

that other activities find this activity important, whereas high "coefficients" would mean that the activity is important to other activities. Tearing here, then, will be a combination of the importance of the activity to other activities and the level of a priori knowledge attributed to each activity.

6.6 Shunt Diagrams

Steward [1981] suggests the use of "shunt diagrams" for making tear selections. Shunt diagrams show all relationships among parameters in the principal circuit including relationships through parameters not included in the principal circuit. Steward [1990] notes that "shunt diagrams give you the structure" within which to supply other semantics such as cost and a priori knowledge during the tearing process. These diagrams are very complicated and tedious when developed by hand. Their use was abandoned for want of the appropriate software during evaluation.

7.0 Conclusions

We have addressed some of the engineering and management issues involved in the design of complex systems. The automotive brake system was used as an example to place these problems in perspective.

After searching the literature for methods to implement systems design concepts, we applied a method developed by Steward [1981] which organizes information using precedent information flows. In particular, the design structure matrix and its development were explained through the use of a short example.

The design structure matrix identifies blocks which further allows the complexity to be analyzed. Blocks, which represent interacting information flows, are of particular interest for they represent complexity. Designers, engineers, and managers may then create an orderly design procedure through tearing and substitution methods. Once a sufficient number of tears have been made, the systems design process can begin.

Our "real-world" example showed that many tears had to be made in order to "solve" the block. In fact, 40 relationships had to be torn. The block allowed us to analyze the interacting decisions in order to choose the least costly set of tears. Once the tearing procedure has been completed, the iterations in the design process can be analyzed and managed so everyone in the organization can follow the design process given a design structure matrix.

We learned that quantifying and gaining consensus on the relationships in the design structure matrix are critical. In addition, the level of detail chosen for the parameters determines the overall complexity of the matrix. Cost acts as a constraint to the given relationships and will eventually couple all parameters as they near their cost constraints (cost relationships could be explicitly placed as parameters).

Several approaches to the implementation of systems design procedures are proposed. In particular, some methods dealing with the block complexity are suggested including the use of a priori knowledge, axiomatics, designed experiments, fuzzy set theory, shunt diagrams, and other methods. Analyzing the block structure and determining where to begin the design process is a fertile area for future research.

We believe the design structure matrix is a practical tool, well-attuned to the

needs and working styles of system designers and product development project managers. With the proper extensions, it can become a widely used methodology for systems design.
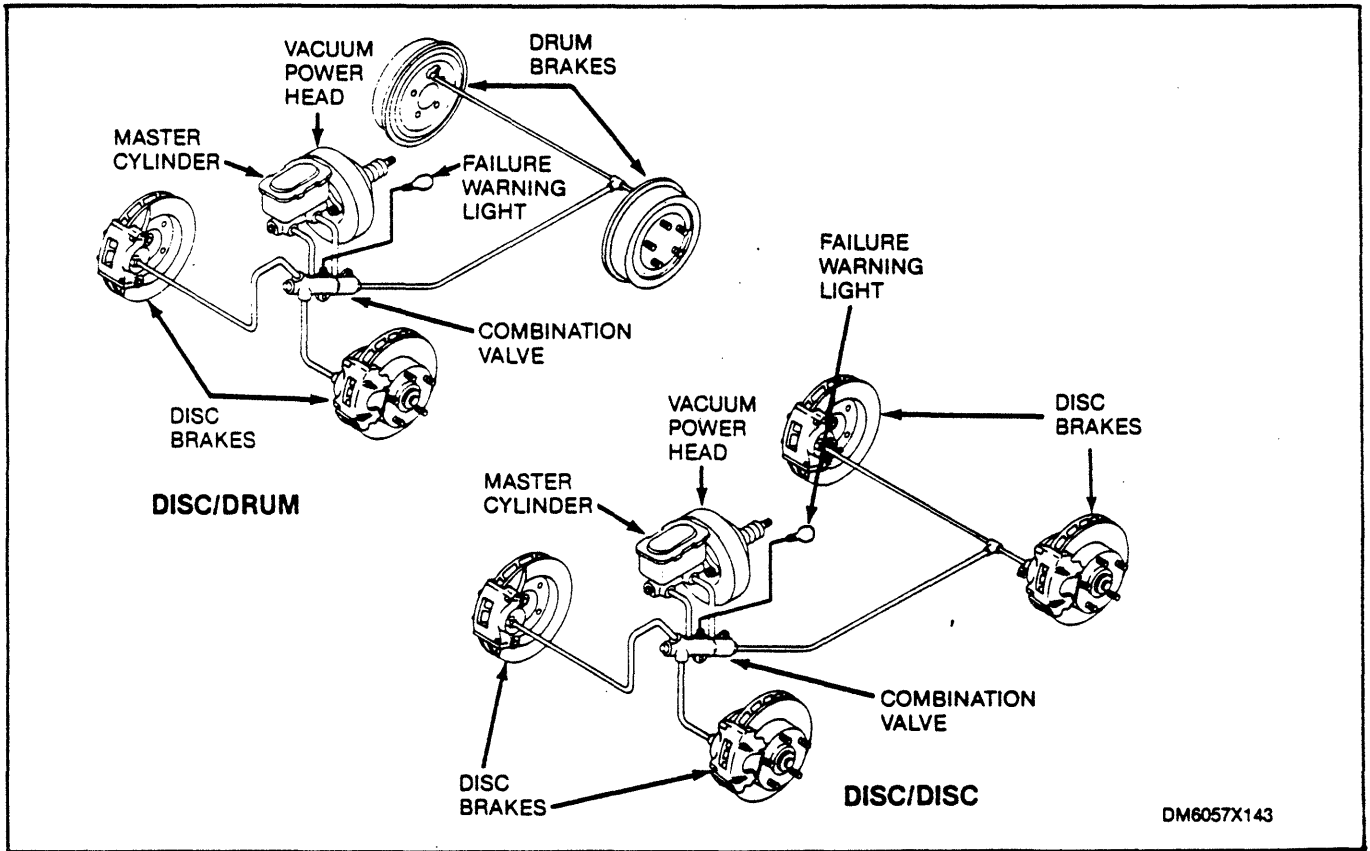
Acknowledgements

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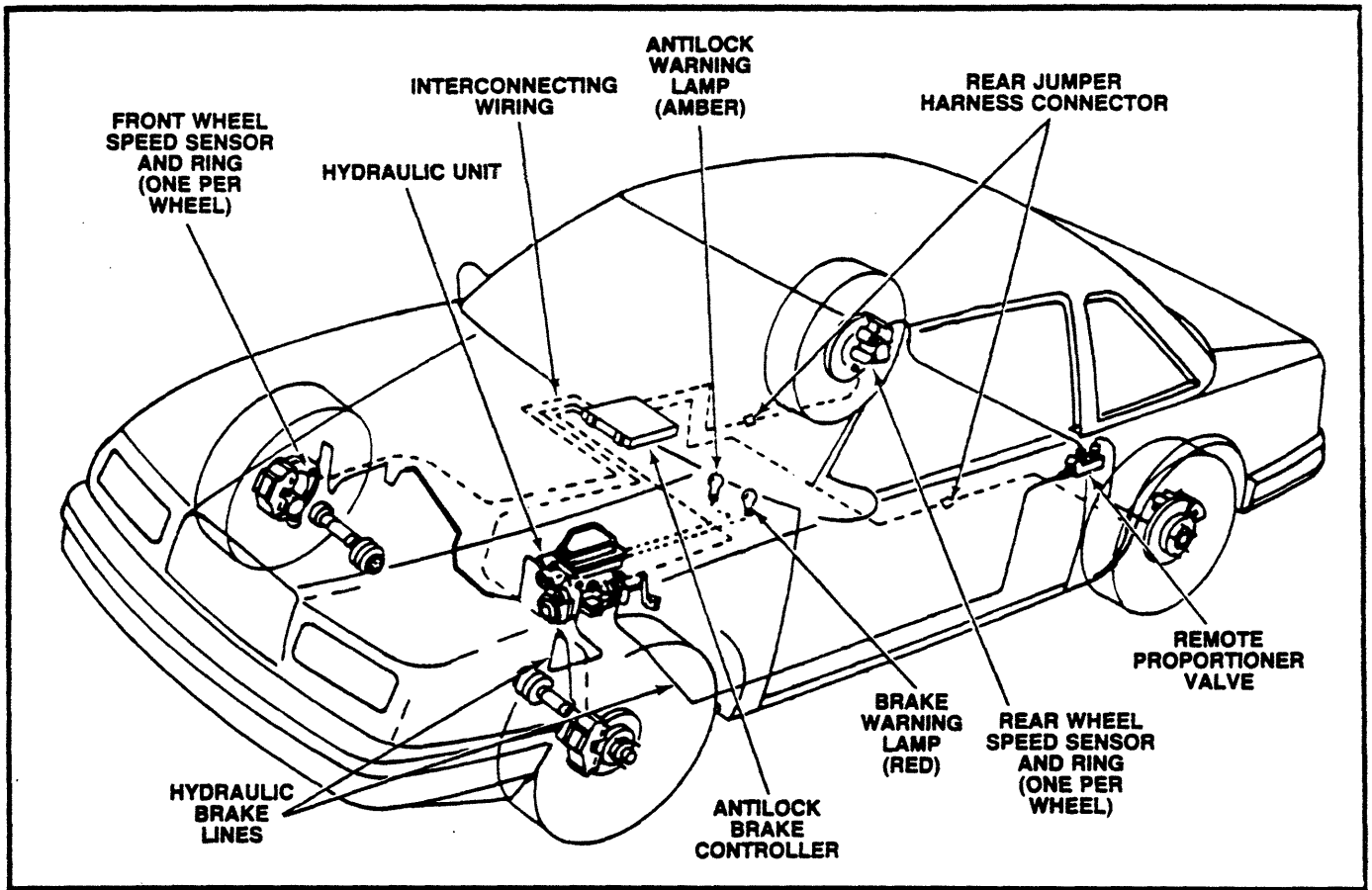
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VACUUM POWER HEAD

DRUM BRAKES

MASTER CYLINDER

FAILURE WARNING LIGHT

COMBINATION VALVE

DISC BRAKES

DISC/DRUM

FAILURE WARNING LIGHT

VACUUM POWER HEAD

DISC BRAKES

MASTER CYLINDER

DISC BRAKES

COMBINATION VALVE

DISC BRAKES

DISC/DISC

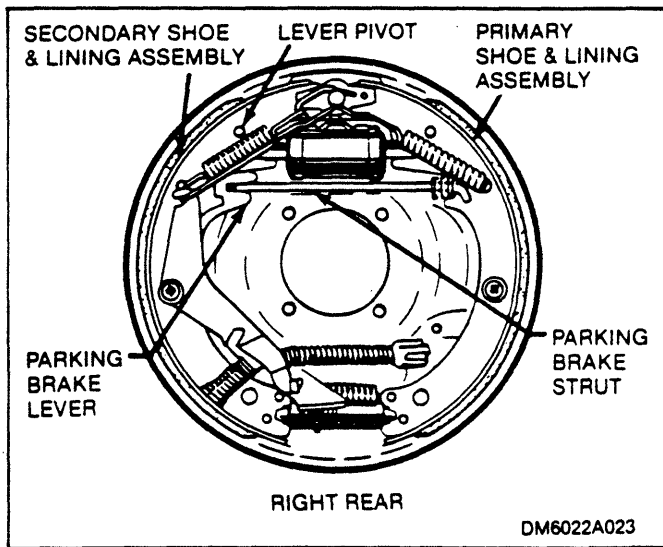DM6057X143

Delco Moraine Antilock Brake System (DM ABS III).

Figure 1-14. Typical Parking Brake Components
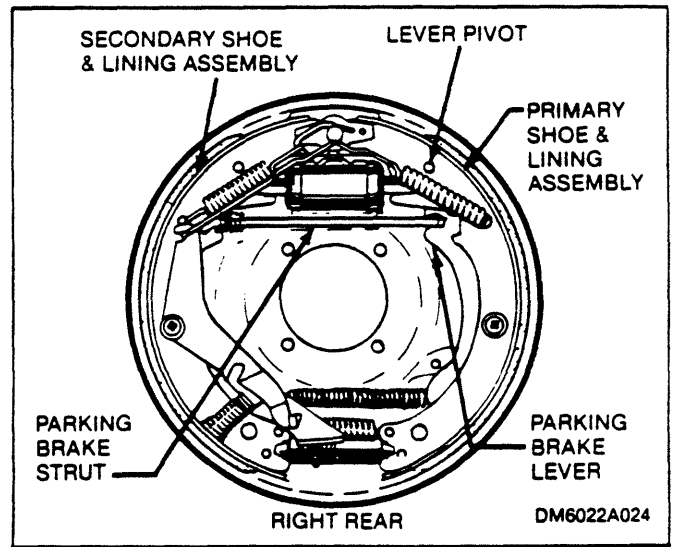
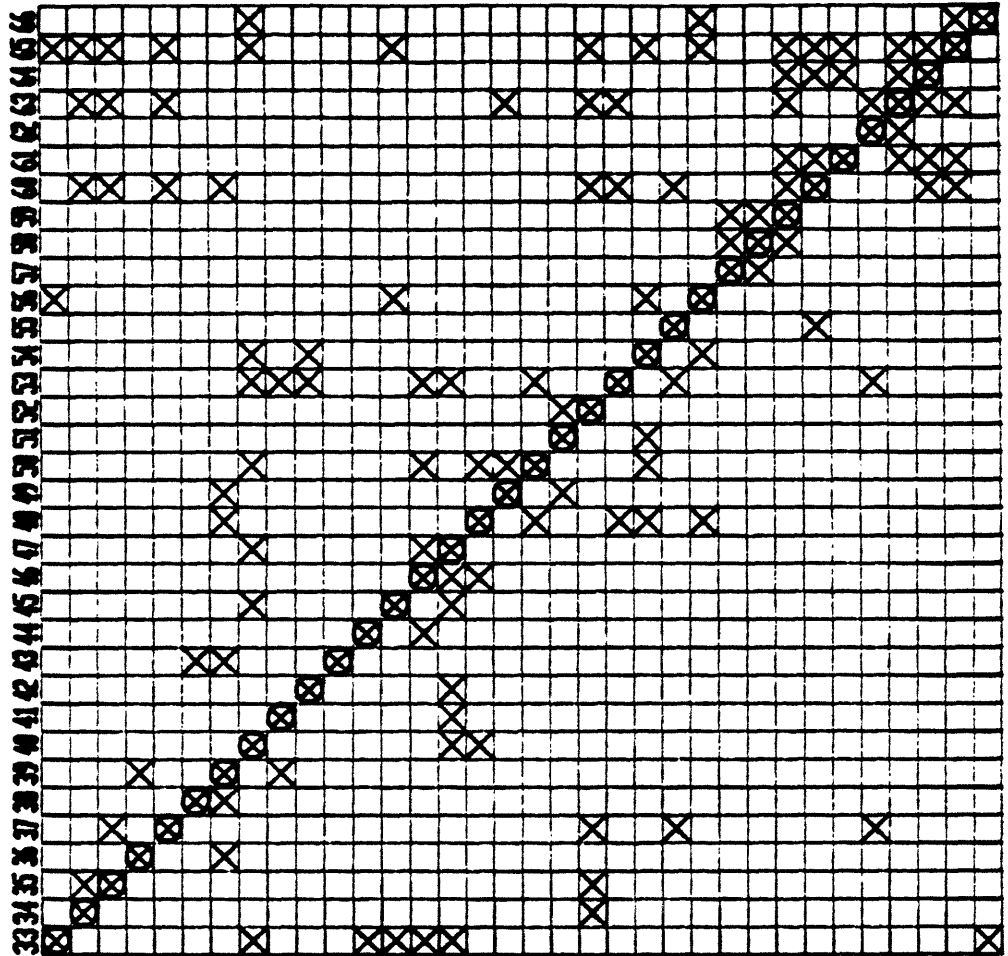Figure 1-15. Parking Brake Components With Rear Entry Parking Brake Cable

33.) VEHICLE ENVELOPE & ATTACHMENT POINTS
34.) PRESSURE AT REAR WHEEL LOCK UP
35.) BRAKE TORQUE VS SKIDPOINT
36.) DRUM MATERIAL
37.) LINE PRESSURE VS BRAKE TORQUE
38.) DRUM MATERIAL (COMPOSITE/CAST)
39.) DRUM - THERMAL ASPECTS
40.) SPLASH SHIELD GEOMETRY - FRONT
41.) BEARING - REAR - HEAT DATD
42.) BEARING - FRONT - HEAT DATD
43.) DRUM BRAKE SIZE
44.) DRUM ENVELOPE & ATTACH PTS.
45.) BEARING ENVELOPE & ATTACH. PTS.
46.) SPLASH SHIELD GEOM. - REAR
47.) ABS SENSOR LOCATION & POS.
48.) AIR FLOW UNDER CAR/WHEEL VENT
49.) WHEEL MATERIAL (ALUMINUM)
50.) WHEEL DESIGN
51.) TIRE TYPE/MATERIAL/ETC.
52.) VEHICLE DECELERATION RATE
53.) TEMPERATURES AT COMPONENTS
54.) ROTOR COOLING COEFFICIENT
55.) LINING - R2, VOL. AND AREA
56.) ROTOR WIDTH
57.) PEDAL ATTACH PTS (PIVOT & PAD
58.) DASH DEFLECTION
59.) PEDAL FORCE (ACTUAL REQUIRED)
60.) LINING COEFFICIENT - REAR
61.) PEDAL MECHANICAL ADVANTAGE
62.) LINING - FRT. VOL & SWEPT AREA
63.) LINING COEFFICIENT - FRONT
64.) BOOSTER REACTION RATIO
65.) ROTOR DIAMETER
66.) ROTOR ENVELOPE & ATTACHMENT PTS