Study of Vehicle Brake Systems Based on Environment-based Design Method

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A Thesis

in

The Department

of

Mechanical and Industrial Engineering

Presented in Partial Fulfillment of the Requirements

for the Degree of Master of Applied Science (Mechanical Engineering) at

Concordia University

Montreal, Quebec, Canada

February 2008

Your file Votre référence
ISBN: 978-0-494-40926-8
Our file Notre référence
ISBN: 978-0-494-40926-8

Abstract

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This thesis is intended to validate and develop a progressive design method — Environment-based Design (EBD). Designers often find them in predicament, where they struggle to develop expertise in the design process. The main reason is that they lack necessary guidance of an ideal design method. Many design methods have been developed, but none has achieved wide acceptance due to the limitations. Fortunately, the advent of Environment-based Design brings us new chance, though some effort still needs to make it optimized.

The case studies, simulative design of early mechanical brake system and analysis of vehicle brake system evolution, were used to explore the validity of EBD. Especially, existing work on Environment-based Design was summarized, by focusing on environment system analysis, design driving force identification, design requirement extraction and analysis, and design concept generation and evaluation. Principles of EBD were comprehensively applied and verified in the simulative design. Also, the vehicle brake system evolution was studied to investigate the laws or trends how products evolves.

The findings indicated that Environment-based Design is a valid design method, which is proved to be an effective tool for formalizing the design process. Design driving forces are conflicts between increasing human needs and current product functions. Design requirements can be obtained by analyzing product environment relations (including conflicts). A quality design concept should satisfy the design requirements, and remove the environment conflicts. Generally, EBD can greatly increase design effectiveness and efficiency.

Acknowledgements

I first take this opportunity to express my heartfelt gratitude to Dr. Yong Zeng, my supervisor, for his constant support and assistance for the duration of my thesis. I benefited a lot from his advice and guidance to accomplish this research.

I am particularly grateful to some professors, such as Dr. Chevy Chen, for instructing me professional knowledge and work ethics, which helped me out of difficulties I encountered in this research work.

I would thank my parents far away in China, whose selfless support has been providing me with incessant spiritual driving force to develop this thesis. Without their backup, I certainly would never finish this task so successfully.

I would deeply appreciate my wife, Hongwei Pei, and my children, Justin Sun and Jane Sun, for their patience, support and understanding. They burdened too much that I should undertake, and lost too much that they should enjoy.

Last but not least, I also would like to acknowledge anyone else who has enabled me to complete this thesis through direct and indirect help. Regretfully, I have no way to mention their names.

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Chapter 1 Introduction

1.1 Background and Motivation

Product design can be defined as the idea generation, concept development, testing and manufacturing or implementation of a physical object or service (Wikipedia, 2007a). Product design is fulfilled in the design process. The skill of product design is obtainable, which means designers can obtain knowledge about how to make product designs through education. A design process that results in a quality product can be learned, provided there is enough ability and experience to generate ideas and enough experience and training to evaluate them (Ullman, 2002). Design methods are scientific approaches which can be followed by designers to achieve valid designs. Designers can improve their skills of designing by an effective way — learning a feasible design method.

Nowadays, many design methods, such as Quality Function Deployment (QFD) (Akao, 1990) and TRIZ (Altshuller, 1988), have been developed. However, it seems that none of them has been widely accepted by designers. The reason why they do not attain extensive acceptance is their distinct limitations. Many designers, especially junior ones, still often find themselves in predicament, where many struggle with developing expertise in the design process (Green and Bonollo, 2004), because they lack the necessary guidance of an ideal design method. Considering the importance of design methods and the state of the art, more efforts should be made in this field, and finally help designers ameliorate their design skills.

A progressive design method, Environment-based Design (EBD) (Zeng, 2004b), originated by Yong Zeng, brings new chance to us. As an innovative design method, the major originality of EBD is that it makes use of analysis of product environment relations to set about design tasks. EBD can help formulate ambiguous design requirements collected from customers into the design specifications with minimal ambiguity and mistakes through a process of the systematic product environmental analysis (Chen and Zeng, 2006).

However, there is still a long way to go to make EBD more optimal, which is exactly the motivation for us to carry out this research. This thesis is intended to make contributions to validate and improve Environment-based Design Method.

1.2 Objectives

This thesis aims to explore the utility value of Environment-based Design, so as to achieve the ultimate purpose of providing designers with an effective design approach to help them improve the design process. Considering that design education is known as a critical way to improve designers' designing skills, and design methods play a key role in design education, we should concentrate on studying the design methodology. To achieve those objectives, the following goals are expected to be accomplished:

- Above all, a critical goal of this thesis is to validate Environment-based Design (EBD), which is the theoretical corner stone of future research work.

- Moreover, the second is to make a comprehensive study to discover the relations between design driving forces, design requirements, design concepts and environment system.
- Also, simulative product designs are used to test the practicability of EBD. Designers can also be presented samples to learn how to use EBD to finish their design tasks without having to constantly recreate the path from start to finished product.
- Finally, a study on design process in terms of evolution of design solutions will be made to reveal the underlying laws of design evolutions.

1.3 Research Approach

This thesis adopts case study associated with theoretical derivation as the main approach to developing the research.

Case study is one of several ways of doing social science research. Other ways include experiments, surveys, multiple histories, and analysis of archival information (Yin, 2003). Case study should be defined as a research strategy, an empirical inquiry that investigates a phenomenon within its real-life context. Case study research means single and multiple case studies, can include quantitative evidence, relies on multiple sources of evidence and benefits from the prior development of theoretical propositions (Yin, 2002).

The vehicle brake system designs are selected as cases to study Environment-based Design. Of all the systems that make up a vehicle, the brake system might just be one of the most important. Over the years of evolution from early mechanical brake system to today's Vehicle Dynamics Control (VDC) system (Carley and Mavrigian, 1998), this critical system experienced many generations of improvements, which just makes it a perfect candidates to develop this research.

1.4 Research Materials

The study mainly includes two parts. The first is to investigate the design process of early mechanical brake system whereas the other is to analyze the evolution of vehicle brake systems.

(1) Simulative Design of Early Mechanical Brake System

Following the summarized Environment-based Design process, simulative design of an early mechanical brake system is made. This research is mainly focused on the following aspects.

A. Summarized Environment-based Design Process

Environment-based Design process was further summarized as follows:

1) Map and analyze the original design problem
2) Analyze the environment system
3) Identify environment Conflicts (Driving Forces)
4) Extract the Design requirements
5) Generate design concepts
6) Evaluate the design concepts
7) Develop detailed Designs

Principles of EBD such as Environment Analysis, Classification of Design Requirements (Chen and Zeng, 2006), and Recursive Object Model (ROM) (Zeng, 2007) are used in the model, more details of which can refer to Chapter 5. The model can provide designers with an easy-to-learn approach to formalizing the design process.

B. Environment Analysis (Identification of Product System)

All the product requirements in a design problem are imposed by the product environment in which the product is expected to work (Zeng, 2004b; Chen and Zeng, 2006). Therefore, product requirements can be defined by environment components. Systematic and thorough environment analyses can make designer clearly understand design problem, find environment conflicts (design driving forces), and extract design requirements correctly.

C. Conflicts Identification (Identification of Design Driving Forces)

Driving force of design is the influence to motivate people to make new designs (Holtzapple and Reece, 2000). Driving forces of design are conflicts between environment components of the product system (Zeng, 2004b). Then something new must be designed to remove the conflicts and balance the system. The design driving forces of early mechanical brake system was analyzed, where dynamic analyses were creatively adopted to study such driving forces.

D. Extraction of Design Requirements

Design requirements are those objectives that must be met in the finished product (Sisson, 2000). Design requirements can be obtained by analyzing product environment relations (including conflicts). After the design requirements are analyzed and classified, some of the most important are selected and considered for subsequent design work.

E. Concept Generation and Evaluation

As an important step of design process, concept design is to generate basic idea to satisfy design requirements. Following the Environment-based Design Process, we simulate to make design concept of early mechanical brake system in detail. A feasible design concept should remove the environment conflicts. The evaluation of design concept is focused on analysis of relations between the environment components.

(2) Analysis of Vehicle Brake System Evolution

A key part of design process is the evolution of design solutions. After studying simulative design of early mechanical brake system, we try to analyze the brake systems in terms of evolution, so as to discover the laws or trends how a product develops in the evolution process.

This analysis is developed from several aspects: environment analysis and conflict identification, design requirement extraction and analysis and concept generation and evaluation.

1.5 Contributions

The contributions of this thesis include:

- Principles of Environment-based Design (EBD) were verified, which would be taken as the theoretical basis for further study.
- A detailed study on the relations between design driving forces, design requirements, design concepts and environment system were precisely analyzed, which will be helpful for designers to solve design problems.
- Environment-based Design (EBD) was integrally used in a product design, which would lay solid foundation for future practice.
- Finally, we attempted to study the design method in terms of evolution to reveal underlying laws or trends of design development, so that enlightenment can be provided to designers for future practice.

1.6 Organization

Chapter 1, Introduction, explains the background and motivation, purpose, methods, and organization of the thesis.

Chapter 2, Literature Review, discusses the previous research in the area related to design methodology.

Chapter 3, Environment-based Design (EBD) Introduction, briefly introduces some relevant principles of Environment-based Design to provide readers with basic idea about the theoretical foundation of this research.

Chapter 4, Review of Vehicle Brake System Evolution, makes a thorough review of vehicle brake systems in history, which can give readers a good chance to understand the case study easily.

Chapter 5, Simulative Design of Early Mechanical Brake System, carries out the simulative design of one vehicle brake system—early mechanical brake system.

Chapter 6, Analysis of Vehicle Brake System Evolutions, analyzes the evolution process of vehicle brake system designs in historical sequence.

Chapter 7, Conclusion and Future Work, summarizes the research results based on the work in this thesis, and suggests some work that should be done in the future.

Chapter 2 Literature Review

To make readers obtain some background knowledge and information to understand this thesis, the literature review will be developed in terms of existing design methods, methods to study design methodologies, and product design evolution.

2.1 Existing Design Methods

Many design methods have been developed to offer designers aids to solve design problems. Two important design methods will be reviewed: Quality Function Deployment （QFD) and Theory of Inventive Problem Solving (TRIZ).

2.1.1 Quality Function Deployment （QFD）

As a flexible and comprehensive group decision making technique, Quality Function Deployment (QFD) originated by Japanese scholars, Drs. Yoji Akao and Shigeru Mizuno in the early 1960s (Wikipedia, 2007b), can be utilized in product or service development, product management, and brand marketing. The aim of QFD is to design products that assure satisfaction and value of customers. By using QFD, the critical characteristics of a new or existing product or service may be accurately concentrated on from the separate viewpoints of the customer market segments, company, or technology-development needs. People can use QFD framework to translate actual customer statements and needs — the Voice of the Customer (VOC) into actions and designs to build and deliver a quality product (Figure 1) (Wikipedia, 2007b).

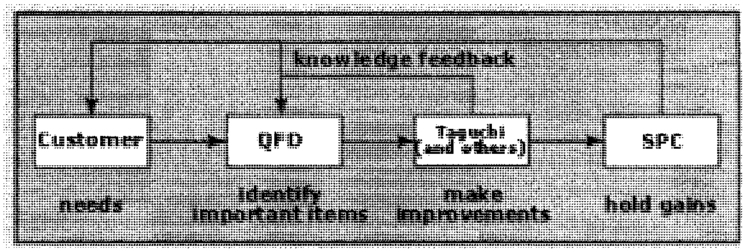


Figure 1 Flow chat of QFD (www.ami.ac.uk, 2007)

(1) Tools and Techniques of QFD

QFD can be used to prioritize customer demands and customer needs (spoken and unspoken), translate these needs into actions and designs such as technical characteristics and specifications, and build and deliver a quality product or service, by focusing on various business functions toward achieving a common goal of customer satisfaction. The technique is also used to identify document competitive marketing strategies and tactics (Kumar, 2007). Many typical tools and techniques are used within QFD as follows.

- **Affinity Diagrams**. To surface the "deep structure" of voiced customer requirements.
- **Relations Diagrams**. To discover priorities and root causes of process problems and unspoken customer requirements.
- **Hierarchy Trees**. To check for missing data and other purposes.
- **Various Matrixes**. For documenting relationships, prioritization and responsibility.
- **Process Decision Program Diagrams**. To analyze potential failures of new processes and services.
- **Analytic Hierarchy Process**. To prioritize a set of requirements, and to select from alternatives to meet those requirements.

- **Blueprinting**. To depict and analyze all the processes which are involved in providing a product or service.
- **House of Quality**. Translate a set of customer requirements, using market research and benchmarking data, into an appropriate number of prioritized engineering targets to be met by a new product design (Figure 2) (Akao, 1990).

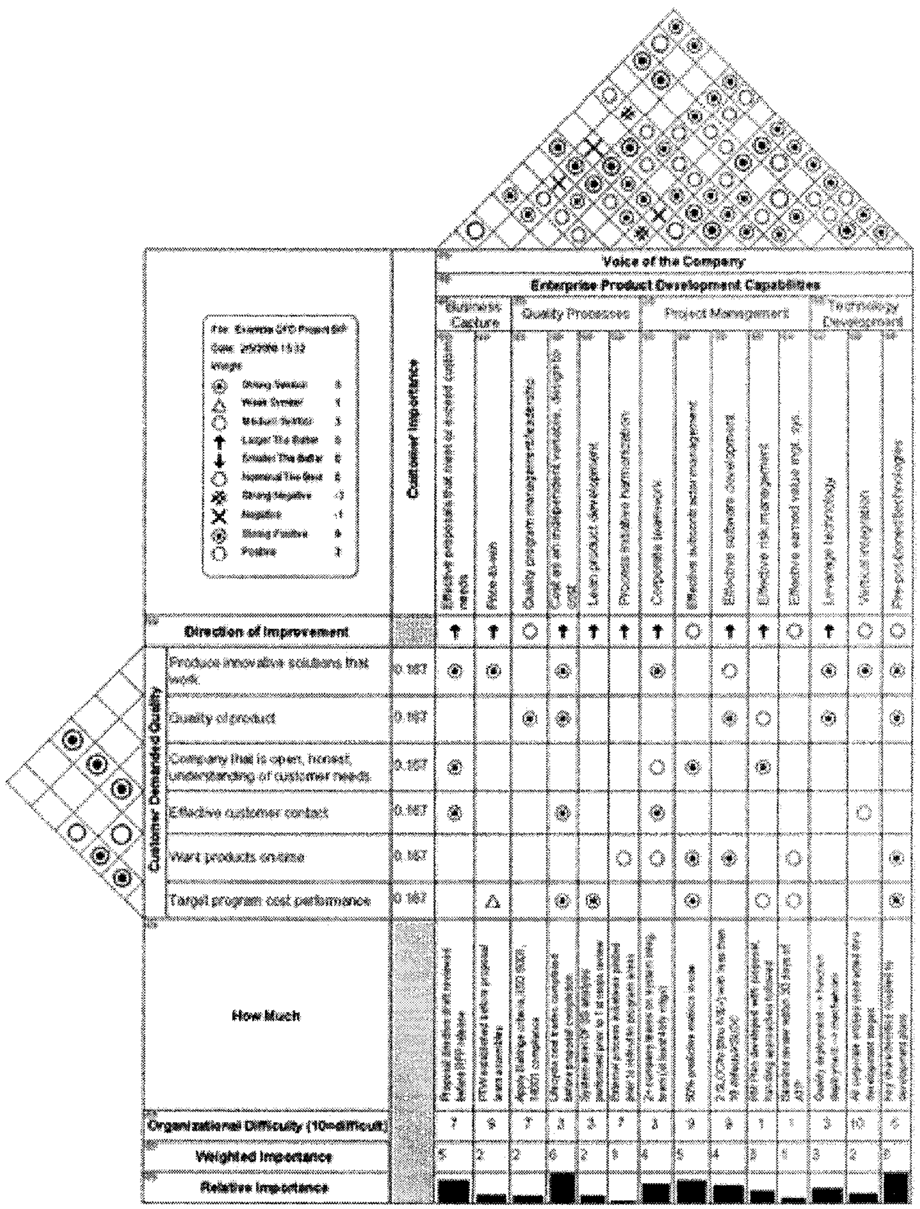


Figure 2 House of Quality (Akao, 1990)

(2) Advantages and Disadvantages of QFD

The strengths of the Quality Function Deployment model are recognized widely. QFD focuses all product development activities on customer needs. It can greatly find customer requirements and maximizes "positive" quality that creates value. The technique also makes invisible requirements and strategic advantages visible. Transparent and visible graphs and matrices can be yielded from the results of QFD, which allows the company to prioritize and deliver on them. The time to market and the cost of design and manufacturing are reduced, and the product quality and customer satisfaction increases simultaneously (Kumar, 2007).

However, the defects of QFD are still worthy of attention. Above all, some problems can occur when QFD, originated in Japan, is applied within the western business environment and culture. Moreover, customer requirements are collected by market survey. But the survey is not easy to be performed properly, which probably results in the failure of the whole product development. Finally, because of the quick change of the needs and wants of customers nowadays, QFD, as a comprehensive system and methodical thinking, can make it more complex to adapt to the change of market needs. (Kumar, 2007)

2.1.2 Theory of Inventive Problem Solving (TRIZ)

As a theory of solving inventive problems, TRIZ was developed by Genrich Altshuller and his colleagues since 1946. It can be used as a methodology, knowledge base, tool set, or model-based technology to create innovative ideas and solutions for problem solving. TRIZ can work as tools and methods to help designers develop problem formulation, system analysis, failure analysis, and patterns of system evolution. In contrast to techniques such as random idea generation based brainstorming, people use this technique to invent new systems, and refine old systems in an algorithmic approach (Wikipedia, 2006a) (Figure 3).

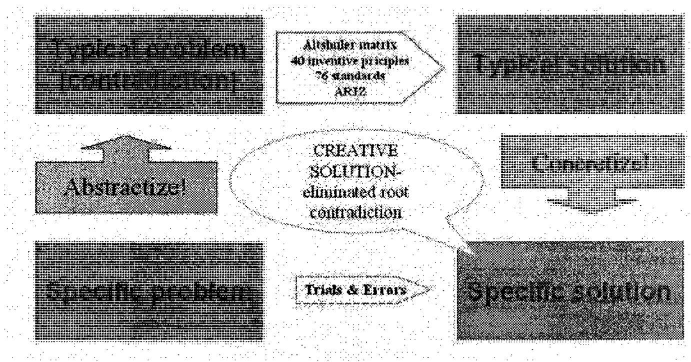


Figure 3 TRIZ way for creative problem solving (Wikipedia, 2006a)

Over the last 50 years, the research has experienced several stages. A lot of patents have been examined, classified by level of inventiveness, and analyzed to seek principles of innovation. More than 40,000 patent abstracts were reviewed by Altshuller to find how innovation took place, and he eventually developed the concepts of technical and physical contradictions, 40 Principles of Invention, several Laws of Technical Systems Evolution, the concept of Ideality of a system and numerous other theoretical and practical approaches. Some essentials of TRIZ are described briefly as follows (Altshuller, 1988; Wikipedia, 2006a).

(1) Identification of a problem: contradictions

Altshuller believed that inventive problems stem from contradictions between two or more elements. That is, more of something desirable also brings more of something less desirable, or less of something else also desirable. He defined two kinds of contradictions: technical and physical or inherent contradictions (Altshuller, 1988).

(2) Inventive principles and the matrix of contradictions

39 system features, 40 inventive principles, and Matrix of Contradictions can be used to remove the contradictions, and then create inventive designs (Figure 4, 5).

1. Weight of moving object
2. Weight of stationary object
3. Length of moving object
4. Length of stationary object
5. Area of moving object
6. Area of stationary object
7. Volume of moving object
8. Volume of stationary object
9. Speed
10. Force
11. Tension, pressure
12. Shape
13. Stability of object
14. Strength
15. Duration of action - moving object
16. Duration of action - stationary object
17. Temperature
18. Brightness
19. Use of energy by moving object
20. Use of energy by stationary object
21. Power
22. Waste of energy
23. Waste of substance
24. Loss of information
25. Waste of time
26. Amount of substance
27. Reliability
28. Accuracy of measurement
29. Accuracy of manufacturing
30. Object affected harmful effects
31. Object generated harmful effects
32. Manufacturability
33. Convenience of use
34. Repairability
35. Adaptability
36. Complexity of device
37. Complexity of control
38. Level of automation
39. Productivity

1. Segmentation
2. Extraction
3. Local Quality
4. Asymmetry
5. Combination
6. Universality
7. 'Nested Doll'
8. Counterweight
9. Prior Counter-Action
10. Prior Action
11. Prior Cushioning
12. Equi-potentiality
13. 'The Other Way Round'
14. Spheroidality
15. Dynamics
16. Partial or Excessive Action
17. Another Dimension
18. Mechanical Vibration
19. Periodic Action
20. Continuity of Useful Action
21. Skipping
22. 'Blessing in Disguise'
23. Feedback
24. Intermediary
25. Self-Service
26. Copying
27. Cheap/Short Living
28. Mechanics Substitution
29. Pneumatics and Hydraulics
30. Flexible Shells/Thin Films
31. Porous Materials
32. Colour Changes
33. Homogeneity
34. Discarding and Recovering
35. Parameter Changes
36. Phase Transitions
37. Thermal Expansion
38. Strong Oxidants
39. Inert Atmosphere
40. Composite Materials

Figure 4 System features and principles of TRIZ (Altshuller, 1988)

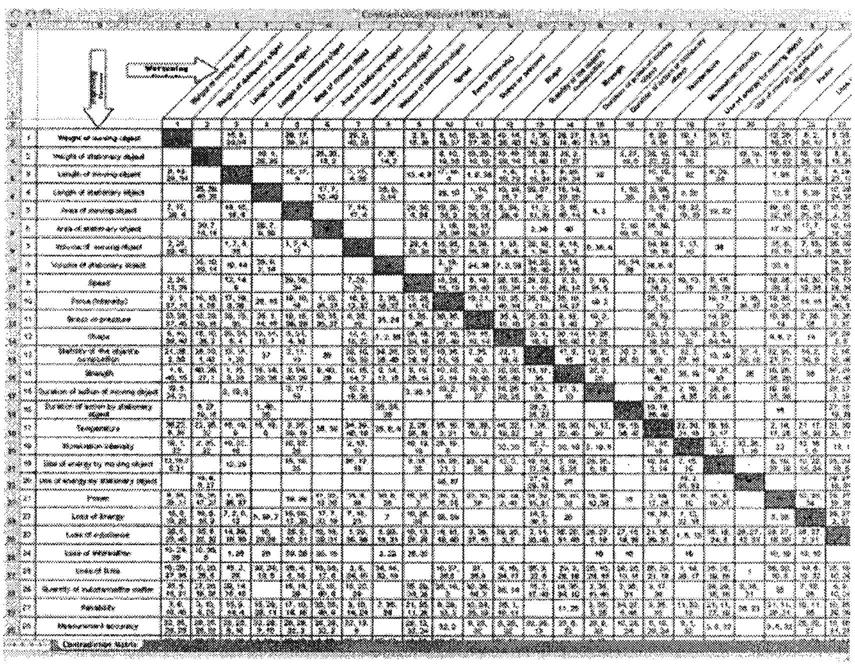


Figure 5 Contradiction matrix of TRIZ (Altshuller, 1988)

(3) Laws of technical system evolution

Utilizing Altshuller's Laws of Technical Systems Evolution, engineers can predict what are the most likely improvements that can be made to a given product (Altshuller, 1988).

(4) Substance-field analysis

Some invention principles involve use of different substances and fields to help resolve contradictions and increase ideality of a technical system (Altshuller, 1988).

(5) Advantages and Disadvantages of TRIZ

Numerous industrial case studies have shown that, TRIZ provides a fast scientific approach to the new product development process by quickly generating new solution concepts. Valeri Souchkov suggested that the following properties of the TRIZ methodology lead to the advantages mentioned above (Savransky, 2000).

- TRIZ helps to organize the fast search for needed knowledge.
- TRIZ provides a systematic access to the previous experience of many generations of inventors.
- To organize and guide the search for proper physical principles, TRIZ pointers to natural phenomena and effects are used.
- The design evolution trends are used for effective problem solving as well as for forecasting the further evolution of a specific design product.
- TRIZ restructures the thinking process of a designer and provides fast access to the needed knowledge (Souchkov, 1999).

On the other hand, critics argue that some drawbacks of TRIZ make the process of learning TRIZ and mastering skills with TRIZ rather slow, and then limit the popularization of TRIZ. Valeri Souchkov gave his ideas about the disadvantages of TRIZ as follows.

- TRIZ does not provide exact recommendations on how to formulate contradictions with respect to a particular problem.
- Identifying an inventive principle can only be done intuitively since no translation technique is available in TRIZ.
- Inventive principles and inventive standards do not propose a solution to a given problem. They only refer to a direction, which was used to solve a similar problem before (Souchkov, 1999).

2.2 Methods to Study Design Methodologies

There are many typical ways to study design methodologies including case study and protocol analysis. Hereby, we discuss these two methods in detail respectively.

2.2.1 Case Study

Case study is an important method to study design methodologies, which involves an in-depth, longitudinal examination of a single instance or event: a case. A systematic way of looking at events, collecting data, analyzing information, and reporting the results can be provided by case study methods. Researchers can subsequently obtain a sharpened understanding of why the instance happened as it did, and what might become important to look at more extensively in the future research as well. Case studies lend themselves to both generating and testing hypotheses (Flyvbjerg, 2006).

Yin defined case study as a research strategy, an empirical inquiry that studies a phenomenon within its real-life context. Case study research means single and multiple case studies, can include quantitative evidence, relies on multiple sources of evidence and benefits from the prior development of theoretical propositions (Yin, 2002).

Case study may be classified into several types, namely, exploratory case studies, critical instance case studies, program effect case studies, prospective case studies, cumulative case studies.

When selecting a case for a case study, researchers often use information-oriented sampling, as opposed to random sampling (Flyvbjerg, 2006). A typical or average case often does not involve the richest in information, but extreme or atypical cases comprise more basic mechanisms and more actors in the studied situation, they often give more relevant information. Moreover, case study should give priority to finding the deeper causes behind a given problem and its consequences rather than describing the symptoms and frequency of the problem. (Wikipedia, 2007c)

2.2.2 Protocol Analysis

Protocol analysis is a known psychological research method that elicits verbal reports from research participants, in which verbal reports of thought sequences are elicited as a valid source of data on thinking. It is also often used in design methodology research by studying human thought process in problem solving to seek the effective methods, which designers can be taught to help them when performing product designs (Ericsson, 2002).

(1) Eliciting Verbal Reports

Protocol analysis method is based on the assumption that subjects are possible to be instructed to verbalize their thoughts in a manner, and the sequence of thoughts mediating the completion of a task is not changed. Therefore, the verbalization of thoughts may be accepted as valid data on thinking (Ericsson, 2002).

Subjects can be asked to "think aloud" when they are performing design tasks, or answering questions asked by the researcher after they finish the design task. By this means, much information about how people deal with the design problem may be obtained (Ericsson, 2002).

(2) Validity of Verbal Reports

By analyzing the information expressed as verbalized thoughts, it is possible to assess the validity of the verbalized information. In Protocol Analysis the verbalized thoughts are compared to intermediate results generated by different strategies that are specified in a task analysis (Ericsson, 2002).

After analyzing the information attained above, the best thinking process to generate creative ideas will be selected and optimized to provide designers effective methods to help them make product designs (Ericsson, 2002).

2.3 Product Design Evolution

Evolution is defined as a gradual process in which something changes into a different and usually more complex or better form in American Heritage Dictionary. In universe, everything experiences evolution, and product designs are no exception. The evolution of design solutions is one significant part of product designs. And product designs evolve in accordance with certain underlying trends. Identifying these trends can be helpful to designers to develop ideal products.

After reviewing thousands of patents, Altshuller put forward his theory: The Laws of Technical Systems Evolution. He subdivided the theory into 3 categories:

- Statics - describes criteria of viability of newly created technical systems.
  - The law of the completeness of the parts of the system
  - The law of energy conductivity of the system
  - The law of harmonizing the rhythms of parts of the system
- Kinematics - define how technical systems evolve regardless of conditions.
  - Law of increasing ideality
  - The law of uneven development of parts of a system
  - The law of transition to a super-system
- Dynamics - define how technical systems evolve under specific conditions.
  - Transition from macro to micro level
  - Increasing the S-Field involvement (Altshuller, 1988)

2.4 Summary

All design methods that have been developed have limitations and none has not received wide acceptance. Therefore, more efforts should be made in the field to help designers improve the design process. After comparing features of the methods to study design methodologies, we selected case study associated with axiomatic approach as the principal method to conduct our research. Altshuller's laws of technical system evolution can in part assist the designers sometimes, but the function is rather limited, so more relevant research is still in need.

Chapter 3 Environment-based Design (EBD): Introduction

This chapter mainly introduces the theoretical background of this thesis. The core theoretical foundation of this thesis is Environment-based Design (EBD) (Zeng, 2004a; Zeng, 2004b). EBD was derived from Axiomatic Theory of Design Modeling (Zeng, 2002). A key method for environment analysis used in EBD is linguistic analysis. Recursive Object Model (ROM) (Zeng, 2007) works as a graphic language to represent all the linguistic elements in technical English. Classification of design requirements is very helpful way for developing design problems. The relevant theories mentioned above will be discussed in detail.

3.1 Axiomatic Theory of Design Modeling

Axiomatic Theory of Design Modeling is a logical tool for representing and reasoning about object structures (Zeng, 2002). It provides a formal approach that allows for the development of design theories following logical steps based on mathematical concepts and axioms. The primitive concepts of universe, object, and relation are used in the Axiomatic Theory of Design Modeling (Zeng, 2002). Their definitions can be found from the Random House Webster's Unabridged Dictionary as follows.

Definition 1: The universe is the whole body of things and phenomena observed or postulated.

Definition 2: An object is anything that can be observed or postulated in the universe.

It can be seen from the two definitions above that universe is the whole body of objects.

Definition 3: A relation is an aspect or quality that connects two or more objects as being or belonging or working together or as being of the same kind. Relation can also be a property that holds between an ordered pair of objects.

$$R = A \sim B, \exists A, B, R, \tag{1}$$

where A and B are objects. A~B is read as "A relates to B". R is a relation from object A to object B. Basic properties of relations include idempotent, commutative, transitive, associative and distributive.

Based on these concepts, the axioms of objects are defined.

Axiom 1: Everything in the universe is an object.

Axiom 2: There are relations between objects.

It can be seen from these two axioms that the characteristics of relations would play a critical role in the Axiomatic Theory of Design Modeling. It is essential to define a group of basic relations to capture the nature of object representation. Two corollaries of the Axiomatic Theory of Design Modeling are used to represent various relations in the universe.

Corollary 1: Every object in the universe includes other objects. Symbolically,

$$A \supseteq B, \forall A \, \exists B, \tag{2}$$

where B is called a sub-object of A. The symbol $\supseteq$ is inclusion relation. The inclusion relation is transitive and idempotent but not commutative.

Corollary 2: Every object in the universe interacts with other objects. Symbolically,

$$C = A \otimes B, \forall A, B \exists C, \tag{3}$$

where C is called the interaction of A on B. The symbol ⊗ represents interaction relation. Interaction relation is idempotent but not transitive or associative and not commutative either. The following rules hold for interaction relations:

$$\begin{aligned} & A \otimes (B \cup C) = (A \otimes B) \cup (A \otimes C) \\ & (A \cup B) \otimes C = (A \otimes C) \cup (B \otimes C) \\ & A \otimes (B \cap C) = (A \otimes B) \cap (A \otimes C) \\ & (A \cap B) \otimes C = (A \otimes C) \cap (B \otimes C) \end{aligned}$$

Based on the Corollary 1 and 2, the structure operation is developed.

Definition 4: Structure operation, denoted by ⊕, is defined by the union of an object and the interaction of the object with itself.

$$\oplus O = O \cup (O \otimes O), \tag{4}$$

where ⊕O is the structure of object O.

The structure operation provides the aggregation mechanism for representing the object evolution in the design process.

Definition 5: The world is an object in the universe, which is made up of two objects: nature and the human thought. The world, nature, and the human thought are denoted by W, N and M, respectively, i.e.

$$W = N \cup M \tag{5}$$

By applying the rules holding for interaction relations and structure operation $\oplus$ defined in Equation (4) to the object W, the structure of the world, $\oplus$W, is

$$\begin{aligned}\oplus W &= \oplus(N \cup M) \\ &= (N \cup M) \cup ((N \cup M) \otimes (N \cup M)) \\ &= N \cup M \cup (N \otimes N) \cup (N \otimes M) \cup (M \otimes N) \cup (M \otimes M) \\ &= (N \cup (N \otimes N)) \cup (M \cup (M \otimes M)) \cup (N \otimes M) \cup (M \otimes N)\end{aligned}$$

Since $\oplus N = N \cup (N \otimes N)$, $\oplus M = M \cup (M \otimes M)$, So the structure of the world, $\oplus$W is got as follows.

$$\oplus W = \oplus(N \cup M) = (\oplus N) \cup (\oplus M) \cup (N \otimes M) \cup (M \otimes N) \tag{6}$$

The four components of the structure of the world, $\oplus$N, $\oplus$M, N$\otimes$M and M$\otimes$N are defined as the natural system, the human rational system, recognition and action respectively.

In accordance to human commonsense, three axioms are developed to identify the nature of the reasoning and recognition processes in the human rational system.

Axiom 3: Human beings are bounded in rationality.

Axiom 4: Human beings do not recognize objects accurately.

Axiom 5: The causal relation is the only plausible relation in all relations between causes and effects.

Five theorems of design are logically derived based on the above five axioms. These theorems cover the construction of an engineering system, the formulation of design requirements, and the model of the design process. They are:

Theorem 1: An engineering system is made up of the product structure, the environment structure, and the mutual relations between the product and the environment.

Theorem 2: In an engineering domain, a limited amount of performance knowledge about a limited number of primitive products exists to represent the causal relations from actions to responses.

Theorem 3: Design requirements can be divided into structural requirements and performance requirements. Structural requirements are constraints on the product structure while performance requirements are constraints on the product performance. These requirements can be decomposed in terms of the product environment in which the product is expected to work.

Theorem 4: A product's performances can be analyzed through performance knowledge by gradually separating each component from the other components.

Theorem 5: Given a collection of design requirements, design solutions can be found by decomposing the product environment implied in the definition of design requirements. Each step of environment decomposition engenders a partial design solution, which redefines the environment and in turn the design requirements. This process halts when all design requirements are satisfied.

3.2 Environment-Based Design Method

The difference between Environment-Based Design Method (EBD) (Zeng, 2004a; Zeng, 2004b) and other design methodologies is that EBD was logically derived from the Axiomatic Theory of Design Modeling (Zeng, 2002), and founded on the recursive logic of design(Zeng and Cheng, 1991). EBD can work as a prescriptive model of design to guide designers throughout the design process from the gathering of customer requirements to the generation and evaluation of design concepts. It is also a descriptive model of the natural design process that illustrates how designers conduct a design task (Yao and Zeng, 2007).

3.2.1 EBD Design Process Flow

As shown in Figure 6, the Environment-based Design process includes three main stages: environment analysis, conflict identification, and concept generation. They work together to generate and refine the design specifications and design solutions progressively and simultaneously. The environment analysis is used to find out the key environment components, where the product exists, and the relationships between the environment components. From the design problem described by the customers, the designer will introduce explicit and implicit environment components that are relevant to the design problem to constitute an environment system. Linguistic analysis (Chen and Zeng, 2006; Wang and Zeng, 2007a) is one of the key methods for environment analysis. By means of environment analysis, conflicts should be identified among the relations between environment components (Zeng, 2004b) . At the last stage - concept generation, a set of key environment conflicts will be chosen and resolved by generating some design concepts. This design process move in cycles until no more unacceptable environment conflicts exist.

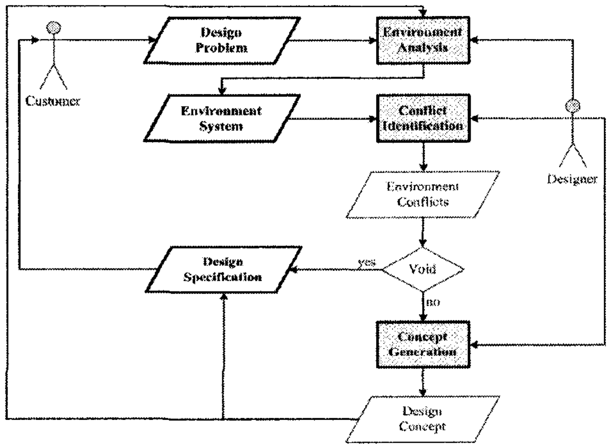


Figure 6 Design Process Flow of EBD (Zeng, 2004a)

3.2.2 Product System

Based on the structure operation (Equation (4)), a product system can be defined as the structure of an object (Ω) including both a product (S) and its environment (E).

$$\Omega = E \cup S, \forall E, S[E \cap S = \Phi], \quad (7)$$

where Φ is the object that is included in any object.

The product system (⊕Ω) can be expanded as follows:

$$\oplus \Omega = \oplus(E \cup S) = (\oplus E) \cup (\oplus S) \cup (E \otimes S) \cup (S \otimes E), \quad (8)$$

where ⊕E and ⊕S are structures of the environment and the product, respectively; E⊗S and S⊗E are the interactions between the environment and the product (Zeng, 2002). A product system can be illustrated in Figure 7.

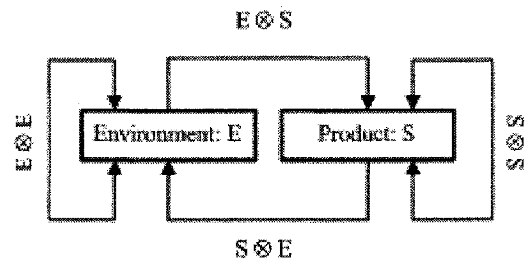


Figure 7 Product system (Zeng, 2002)

3.2.3 Evolution of Design States

In the design process, any previously generated design concept can be indeed seen as an environment component for the succeeding design. As a result, a new state of design can be defined as the structure of the old environment (E_i) and the newly generated design concept (S_i), which is a partial design solution (Figure 8) (Zeng, 2004b).

$$\oplus E_{i+1} = \oplus(E_i \cup S_i). \quad (9)$$

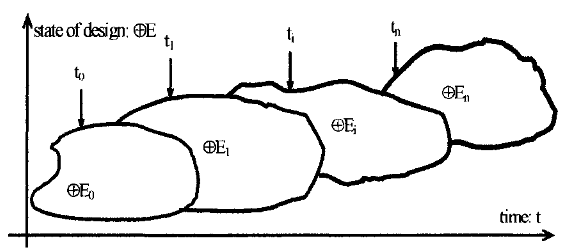


Figure 8 Environment based design: mathematical model (Zeng, 2004b)

The evolution from the design state $\oplus E_i$ to the design state $\oplus E_{i+1}$ is governed by the following design governing equation (Zeng, 2004b),

$$\oplus E_{i+1} = K_i^s(K_i^e(\oplus E_i)), \quad 10)$$

where K_i^s and K_i^e are evaluation and synthesis operators (Zeng and Gu, 1999a), respectively.

The two operators K_i^s and K_i^e correspond to two major phases in the design process: synthesis and evaluation. The synthesis process is responsible for proposing a set of candidate design solutions based on the design problem. It stretches the state space of design. The evaluation process is used to screen candidate solutions against the requirements in the design problem. It folds the state space of design. The interaction of both synthesis and evaluation processes gives rise to the final balanced design solutions, which can be illustrated in Figure 9.

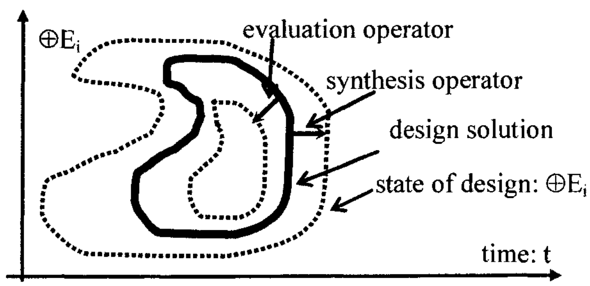


Figure 9 Design state space under two operators (Zeng and Gu, 1999a)

The EBD process solves the design governing equation by following the procedures below (Zeng, 2004b):

Step 1: Environment analysis: define the current environment system $\oplus E_i$.

$$\oplus E_i = \oplus(\bigcup_{j=1}^{n_c} E_{ij}) = \bigcup_{j=1}^{n_c}(\oplus E_{ij}) \cup \bigcup_{j_1=1}^{n_c}\bigcup_{\substack{j_2=1 \\ j_2 \neq j_1}}^{n_c}(E_{ij_1} \otimes E_{ij_2}). \tag{11}$$

Step 2: Conflicts identification: identify conflicts C_i between environment components.

$$C_i \subset \bigcup_{j_1=1}^{n_c} \bigcup_{\substack{j_2=1 \\ j_2 \neq j_1}}^{n_c} (E_{ij_1} \otimes E_{ij_2}). \tag{12}$$

Step 3: Concept generation: generate a design concept s_i by resolving a group of chosen conflicts. The generated concept becomes a part of new product environment for the succeeding design. The design process continues with new environment analysis until no more undesired conflicts exist, i.e., $C_i = \Phi$.

$$\exists c_{ik} \subset C_i, c_{ik} \rightarrow s_i, \oplus E_{i+1} = \oplus(E_i \cup s_i). \tag{13}$$

3.2.4 Theorems Implied in EBD

There are four theorems implied in EBD: Theorem of recursive logic of design, Theorem of source of product requirements, Theorem of dynamic structure of design problem, and Theorem of design driving force.

(1) Theorem of recursive logic of design. A design solution must pass an evaluation defined by the design knowledge that is recursively dependent on the design solution that is to be evaluated (Zeng and Cheng, 1991).

Based on this theorem, a design process is composed of a series of design states defined by both product descriptions and product requirements, as is shown in Figure 10.

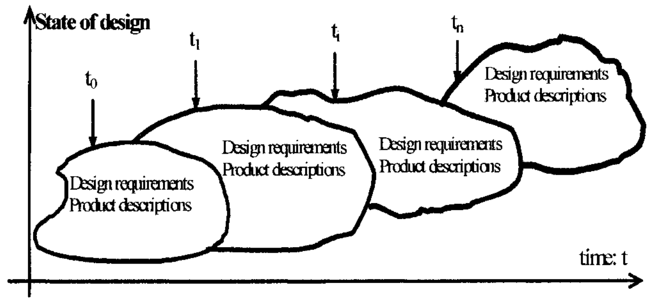


Figure 10 Evolution of the design process (Zeng, 2004b)

(2) Theorem of source of product requirements. All the product requirements in a design problem are imposed by the product environment in which the product is expected to work (Zeng, 2004b; Chen and Zeng, 2006).

This theorem implies that the driving force of a design process comes from environment, which includes natural human, and built environments (Zeng, 2004b); therefore, product requirements can be defined by environment components in which the product is expected to work. Based on this theorem, product requirements are included in the environment structure ⊕E, which is the state of design and is defined as in equation (9).

The most important implication of this theorem is that the purpose of design is to change environment if the combination of conflicts among the components in the current environment produces enough driving forces, which can be derived from ⊕E, to start a design process.

(3) Theorem of dynamic structure of design problem. In the design process, design solutions to a design problem may change the original design problem, if the design solutions are different from their precedents, either by refinement or by alteration (Zeng, 2004b).

(4) Theorem of design driving force. The driving force behind the design process is the undesired combined conflicts existing in an environment system. A design process continues until no such conflicts exist. This theorem is illustrated in Figure 8.

3.3 Recursive Object Model

Recursive object model (ROM) developed by Zeng (Zeng, 2007) is a graphic language representing all the linguistic elements in technical English, derived from Axiomatic Theory of Design Modeling. Design problems are represented by language descriptions and design processes are described by designers in natural language. Language is a symbol system human beings used to describe the universe (Turner, 1971). The symbols in a language may also fulfill certain structural functions in the language pattern so that ideas and objects can be combined to form more complex meanings (Turner, 1971). ROM can be used to collect, organize, interpret, and analyze the characteristics by inferring from multiple object relationships implied in the natural language. As can be seen from (Table 1), two objects and three relations are included in the ROM.

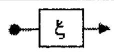
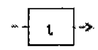
Type		ROM symbols	Description
Object	Object		Everything in the universe is an object.
	Compound Object		It is an object that includes at least two objects in it.
Relations	Constraint Relation		It is a descriptive, limiting, or particularizing relation of one object to another.
	Connection Relation		It is to connect two objects that do not constrain each other.
	Predicate Relation		It describes an act of an object on another or that describes the states of an object.

Table 1 Symbols used in ROM (Zeng, 2007)

3.4 Design Requirement Elicitation and Analysis

After environment conflicts are identified, they can be expressed as design requirements, which are easier to understand and operable. It is of great importance accurately and sufficiently gathering design requirements, because a qualified design concept must satisfy design requirements. An effective method can greatly help designers to elicit those design requirements correctly.

3.4.1 Generic Inquiry Process for Eliciting Design Requirements

Any design process starts with a description of a design task, which is often described in natural language by customers. Therefore, the design task is customer oriented and may be ill-defined while the requirements elicitation process should generate formal and structured descriptions, which are engineering oriented. Asking the questions is an effective way to identify the customer's real intent and to define a relatively more complete list of product requirements (Wang and Zeng, 2007b)

As shown in Figure 11, A generic inquiry process for eliciting product requirements (Wang and Zeng, 2007b) has been proposed,. The process can be divided into the eight steps as follows.

Step 1: Create ROM diagram

Designer transforms the original design problem described by natural language into a ROM diagram using a ROM analysis tool. This will enable the designer to understand the design problem more clearly.

Step 2: Generate generic questions

In this step, designer analyzes each object in the ROM diagram to find out the objects that need to be identified or clarified further and generates some candidate questions based on a set of predefined rules and question template. Then these questions will be chosen to ask. These questions will help customers to understand and to clarify their real intent.

Step 3: Collect answers

Designer collects the answers to the questions which are generated from Step 2 by looking up dictionary or knowledge base, searching on internet, or collecting from the customer.

Step 4: Repeat Step 1 to 4 until no more generic questions can be asked

The answers collected in Step 3 are analyzed iteratively as new ROM diagrams at Step 1. Then these new ROM diagrams are identified or clarified by asking questions at Step 2. Thereafter, ROM diagrams are merged into the original ROM diagram in the ROM tool based on a set of predefined rules.

At the end of the step, the explicit design problem description is extended further. The recursive process will be shown more clearly in the algorithmic description of the procedures.

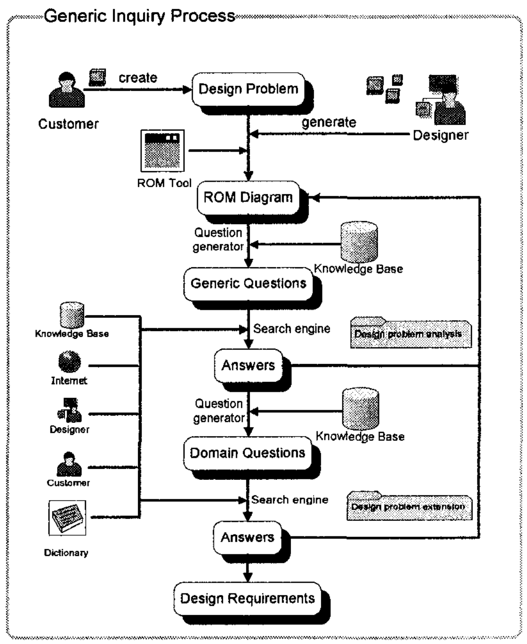


Figure 11 Generic inquiry process (Wang and Zeng, 2007b)

Step 5: Generate domain specific questions

The explicit design problem description above may not exactly and completely define the design problem. Designer needs to elicit more implicit environment information about the design problem. In this step, designer analyzes the relationships between the objects in the updated ROM diagram and generates a set of questions that should be answered at each stage of the design. Meanwhile the sequence for asking these questions should be determined automatically or manually based on a set of predefined rules.

Step 6: Collect answers to the questions generated in Step 5

This step is similar to Step 3

Step 7: Repeat Step 1 to 7 until no more domain questions can be asked

To collect complete domain dependent product requirements and to analyze the implicit domain dependent product requirements iteratively in Step 1 to 7 may ensure that the domain dependent product requirements are accurate.

Step 8: Output the updated design problem description

The process presented above can be alternatively represented by the following algorithmic process described in pseudopodia. The whole process is made up of two sub-processes, which are design problem analysis and design problem extension (Wang and Zeng, 2007b).

3.4.2 Classification of Design Requirements

Effective analysis and management of design requirements are helpful to accurately find those design requirements that are most important and must be satisfied. To be easy and convenient to analyze and manage, design requirements can classified into different types in terms of phrases of product cycle life or of levels of priorities.

(1) Events in Product Cycle

Design is a repetitive process of generating requirements by the demand side and satisfying it by the supply side. Both demand side and supply side include several participants, each of which performs different functions in the product life cycle (Chen and Zeng, 2006).

The product life cycle can be divided into seven kinds of events, which are design, manufacture, sales, transportation, use, maintenance, and recycle (Figure 12).

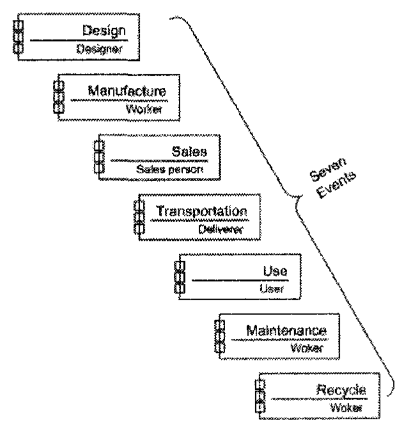


Figure 12 Seven events in product life cycle (Chen and Zeng, 2006)

According to the structure of design problem, the preceding seven events represent seven individual environment components, namely, design, manufacture, sales, transportation, use, maintenance, and recycle. They are denoted by E_{ds}, E_{mf}, E_{sl}, E_{tp}, E_{us}, E_{mt}, and E_{rc}, respectively (Chen and Zeng, 2006).

$$E = E_{ds} \cup E_{mf} \cup E_{sl} \cup E_{tp} \cup E_{us} \cup E_{mt} \cup E_{rc}. \tag{14}$$

(2) Levels of Design Requirements

In order to mange product requirements, they are categorized into eight levels: natural laws, social law and regulations, technical limitation, cost, time and human resource, basic functions, extended functions, exception control level, and human-machine interface (Figure 13). In this pyramid-like model, those requirements at the lower levels have higher priority in developing a design solution. And those meeting the requirements at the highest level are called high usability products (Chen and Zeng, 2006).

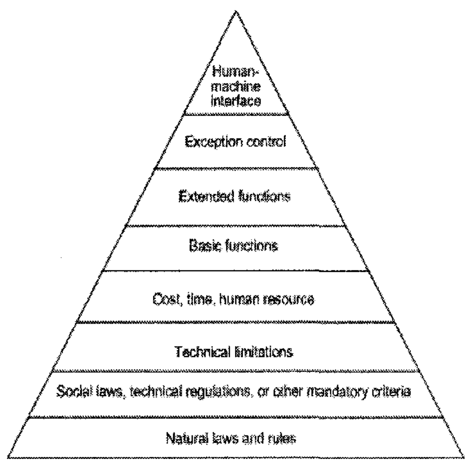


Figure 13 Eight levels of design requirements (Chen and Zeng, 2006)

All products must be built based on natural laws and rules. In the second place, a designer must follow social laws, regulations and other mandatory criteria. Then, the designer takes technical limitations into consideration when design solutions are formulated, after which designer has to make sure that the budget, schedule and human resource demand are within an acceptable range. These four levels of requirements are the basic conditions for a product to be born and exist physically in its environment. On the basis of satisfying these four levels of requirements, designers may start to realize basic functions. After all basic functions achieve, designers can start to consider extended functions, exception control, and human-machine interfaces (Chen and Zeng, 2006).

3.5 Summary

The theoretical background for this thesis research is briefly introduced in this chapter. Axiomatic Theory of Design Modeling provides designers with a logical tool for studying design activities. Environment-based Design developed based on Axiomatic Theory of Design Modeling is a new design method. EBD provides the theoretical foundation of explaining the observations and properties from design activities.

Chapter 4 Review of Vehicle Brake System Evolution

Motor vehicles have served people as the primary means of transportation for several decades. The brake system is considered one of the most important systems making up of a motor vehicle. From the early mechanical brake system to today's Vehicle Dynamics control (VDC) system, this critical system underwent several generations of evolution, which just makes it a perfect candidate as the case to develop this research. To help readers understand this thesis; it is necessary to summarize how brake systems evolved.

4.1 Early Mechanical Brake System

The early mechanical brake system was designed for early motor vehicles with steel rimmed wheels (Figure 14). It worked almost in the same way as those on the horse drawn carriages (Wikipedia, 2006b).

Figure 14 Early motor vehicle with steel tires (www.shimbo.co.uk, 2000)

Typically, such a brake system consisted of curved wooden blocks (brake shoes), levers, rods, pivots, and cables. Those levers, rods, pivots and cables were arranged in certain way to be a leverage operation system, as shown in Figure 15. The driver manipulated the simple leverage operation system from the driver's seat by pulling the handle or pressing the foot pedal, and then curved wooden blocks bore against the steel tires to prevent the wheels from rotating (Wikipedia, 2006b).

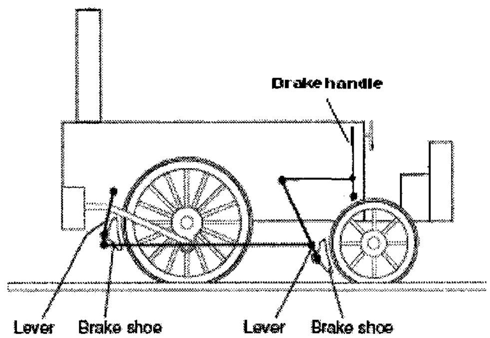


Figure 15 An early mechanical brake system (Hasegawa and Uchida, June 1999)

As the earliest vehicle brake system, the early mechanical brake system was born together with the first self-propelled road vehicle invented by Nicolas Joseph Cugnot in 1769. It was the ancestor of modern vehicle brake systems, and had basic function to brake a vehicle.

4.2 External Band Brake System

Since 1895, the Michelin Brothers attempted to renovate the vehicle wheels by replacing steel rimmed tires with the pneumatic rubber ones (Figure 16). The new popular pneumatic rubber tires were not suitable for early mechanical brakes because of the poor wear property of new rubber tires, so designers had to think of a new brake system (Wikipedia, 2006b).

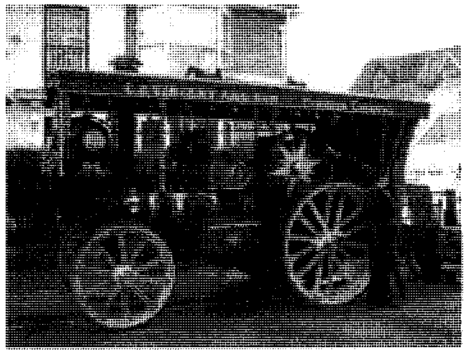


Figure 16 An early vehicle with pneumatic rubber tires (www.shimbo.co.uk, 2000)

A new brake system, called external band brake system, was developed to suit the replacement of tires. Devices were designed to apply the friction force to the axle or transmission shaft, or to a drum attached on them (Figure 17). The driver operated this type of brake by operating a handle lever or pressing a foot pedal. More friction was produced to give the vehicle greater retardation by higher force applied by the driver to the handle or pedal. Such a brake system was often made up of drums, metal bands with lining, and a mechanical operation system composed of levers, rods, pivots, and cables etc (Wikipedia, 2006b).

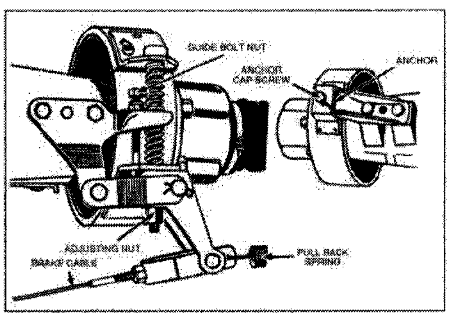


Figure 17 An external band brake (Carley and Mavrigian, 1998)

4.3 Internal Expanding Shoe Brake System

The structure of external band brake was open, so rain or snow was easy to enter the space between the brake bands and drums, and worked like lubricant to cause loss of braking efficiency. Road dirt in the space easily caused rapid wear of brake band linings. "Automatic" braking application took place occasionally due to drum expansion (Wikipedia, 2006b).

The internal expanding shoe brakes were developed to avoid those problems of external band brakes. The new brakes were protected from weather and dust by their closed structure, where the internal brake shoes were inside an external brake drum (Figure 18).

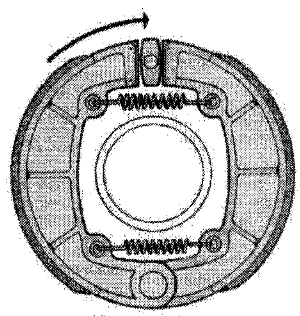


Figure 18 An early internal expanding shoe brake (Dan, 2007)

The first internal expanding shoe brake seemed to appear with Louis Renault in 1902, and the basic principle remained to present, although much evolution experienced (e.g. operation system developed from mechanical to later hydraulic means (Figure 19)) (Wikipedia, 2006b).

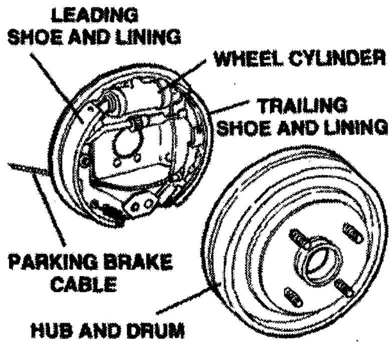


Figure 19 Mondern hydraulic drum brake (www.procarcare.com, 2007)

4.4 Hydraulic Brake System

Originally, motor vehicles were equipped with brakes operated by mechanical systems consisting of levers, rods, pivots and cables. Such a brake system had much trouble in keeping in good operating order for the linkage system. It was also difficult in equalizing brake pressure on the wheels. Problems were well solved by the introduction of the hydraulic system, where fluid was used to transfer the force applied to the brake pedal (Wikipedia, 2006b).

Hydraulic brake systems make use of the fact that liquid is incompressible, and that when pressure is applied to a closed system, it is exerted equally in all directions. Also, a hydraulic system can be used to increase or decrease force or motion (Pascal's law).

All the cylinders and pipe lines form one closed hydraulic system filled with brake fluid. The function of a master cylinder, which has a single piston, is to generate hydraulic pressure by depressing brake pedal. Wheel cylinders, each of which has 2 pistons, are used to apply forces to the brake shoes. The brake shoes are forced to expand and bear against the drums to retard the vehicle (Figure 20) (Wikipedia, 2006b).

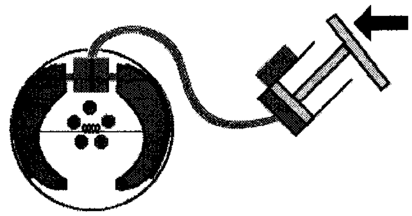


Figure 20 Priciple of hydraulic brake system (www.allstar.fiu.edu, 2006)

The hydraulic brake system greatly simplified the job of providing balanced four-wheel braking, since the pressure is transmitted from the master cylinder to the pistons of all wheel cylinders equally without weakening and time lag. As a result, pressures are applied to all brake shoes identically and simultaneously. By changing the areas of pistons of master cylinder and wheel cylinders, hydraulics also reduced the required effort amount applied to the pedal for braking, which made for easier braking and safer driving (Figure 21).

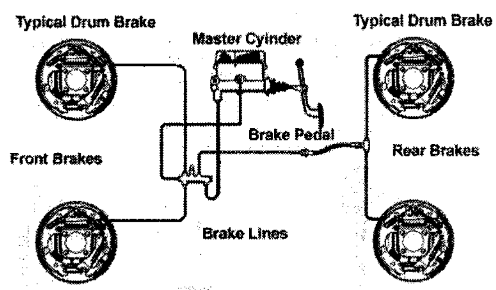


Figure 21 Hydraulic 4 drum brake system (Ofria, 2000)

In 1920, Duesenberg was first production vehicle equipped with hydraulic brakes. Soon they were adopted and developed by all vehicle manufactures (Carley and Mavrigian, 1998).

4.5 Power Brake System

Power-assisted braking is known as the next big innovation in brakes. Power brakes use a booster and usually engine vacuum or hydraulic pressure to assist brake pedal application. The booster (assisting mechanism) is often located between the brake pedal linkage and the master cylinder. When the driver presses the brake pedal, the brake booster helps push on the master cylinder's piston (Figure 22) (Duffy, 2004).

Power brake systems can dramatically reduce the effort amount required for braking, which made for easier braking and safer driving (Figure 23).

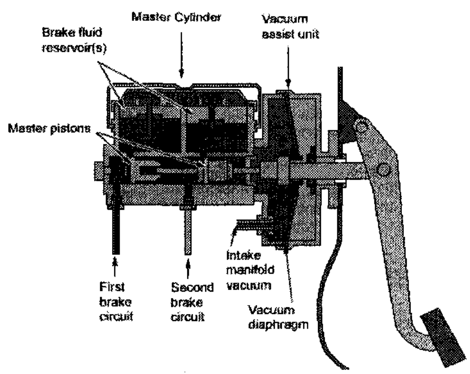


Figure 22 "Master-Vac" power brake booster (Bicking and Switch, 2006)

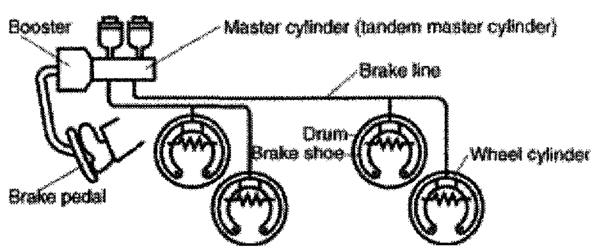


Figure 23 Power hydraulic drum brake system (www.mitsubishi-fuso.com, 2007)

Cadillac first offered vacuum assisted power brakes in 1930. The original "Master-Vac" power brake booster patented in the 1950s by Bendix became the predecessor to today's vacuum booster. As disc brakes were becoming more common, the power booster, a popular option in the 1960s, became standard equipment on most vehicles by the mid-1970s. Today power brakes have already been standard equipment on nearly all motor vehicles. (Carley and Mavrigian, 1998).

4.6 Disc Brake System

Although drum brake was considered a kind of good vehicle brakes, its defects showed more and more apparent, as motor vehicles became faster and heavier. First, its ability of dissipating heat is not satisfying. A tremendous amount of mechanical energy is transformed into heat when braking is applied, which requires good cooling ability to prevent fading. Nevertheless, the enclosed structure design of drum brakes makes it impossible to cool well, because heat generated inside drums can only dissipate on the outer surface of the drums. Moreover, one more defect of drums is trapping water. When a vehicle passes though a puddle, water can enter and stay in the drums. Water inside the drums will act as lubricant to prevent the shoes from grabbing the drum, which leads to loss of braking efficiency (Carley and Mavrigian, 1998).

Disc brakes appeared with their advantages. First, disc brakes have sufficient cooling ability. The exposed flat faces and the addition of fins and vents between the faces of the rotor guarantee good ability to dissipate heat. Second, the open structure makes them not trap water, which provides a safe design for wet weather driving. Third, self-adjusting ability of disc brakes simplifies the design by eliminating self adjusters or periodic adjustment.

The main parts of a disc brake include a caliper, brake pads and a brake disc. A hydraulic piston is installed inside the brake caliper. The brake pads mounted within the jaws of a caliper grips a brake disc to provide the necessary friction (Figure 24).

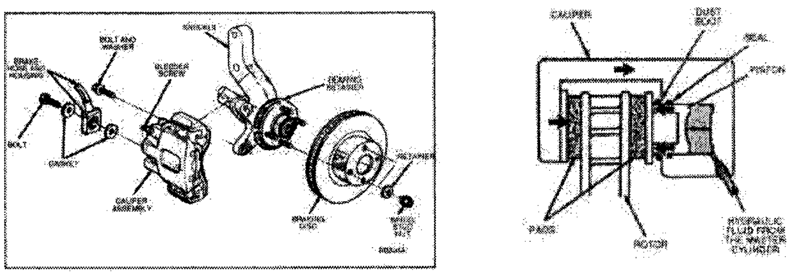


Figure 24 Assembly of disc brake (Carley and Mavrigian, 1998)

A drum brake costs less than a disc brake, but the disc brake performs better than the drum brake. Also, the front brakes provide 60-70% braking force for the vehicle, while the rear ones supply only 30-40% (Duffy, 2004). So disc brakes were often used in the front to undertake most braking, and drum brakes were adopted in the rear to save cost and allow the use of a simpler parking brake. To this day, this front disc/rear drum arrangement is still popular, as it provides the best composite between cost and performance. Sports models and high-end luxury sports sedans tend to use four-disc brake systems (Figure 25).

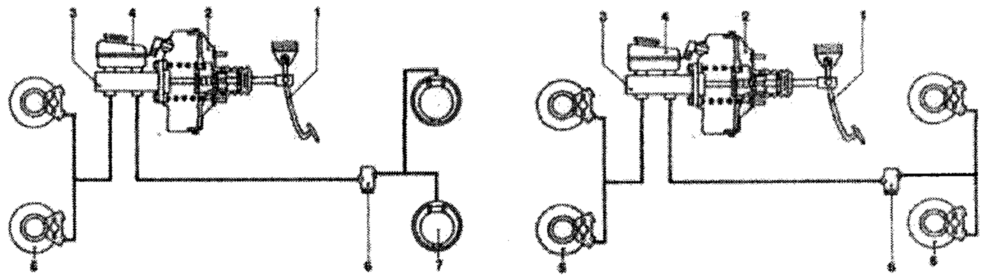


Figure 25 Modern disc (drum) brake systems (www.e-z.net, 2000)

It took several decades for the disc brakes to experience from invention to wide use. An electric-powered car was equipped with the primitive disc brakes as early as 1898. However, disc brakes were not widely used until the late 1960. In Europe, they were adopted on sports cars (Triumph and Jaguar) in 1956. But disc brakes were first offered as standard on the 65 Corvette and optional on the 65 Mustang GT in 1965 (Carley and Mavrigian, 1998).

4.7 Antilock Brake System (ABS)

The invention of electronic antilock brake system (ABS) solves problems happening at wheel lockup. When the wheels lock up in a panic stop, the vehicle can not be stopped as soon as it is capable of stopping, since the most efficient braking force occurs just before wheel lockup. Also, losing of all steering control takes place at wheel lockup in an emergent braking. Finally, the tires will be worn much more than normal during an extended skid, and an annoying thumping sound follows simultaneously (Figure 26) (Ofria, 2000).

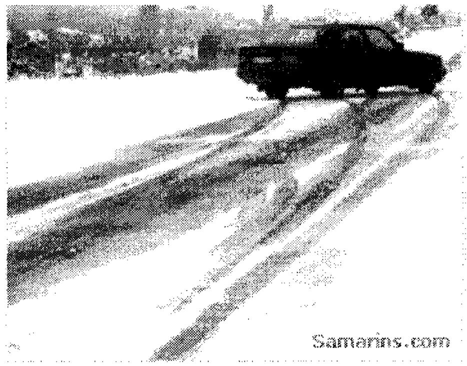


Figure 26 Problems at wheel lockup (www.samarins.com, 2007)

ABS rapidly pumps the brakes whenever the system detects that any of wheels is becoming locked up. Speed sensors monitor the speed of all wheels and send information to the electronic control unit (ECU). Once any wheel, which has stopped rotating or is turning far slower than the rest, is detected, the scavenge pump will momentarily receive a signal from ECU to release and reapply (or pulse) the hydraulic pressure to the affected wheel to allow them to continue rotating. The frequency of this "pumping" of the brake fluid is ten or more times per second, which a human being has no way to reach manually, no matter how experienced he or she is. Always, only the wheel that is locking up will be pumped, while the rest are available to full braking pressure. By minimizing wheel lockup and skidding, ABS allows the driver to maintain steering control when braking hard, and keep the vehicle straight and stable to avoid the chance of getting sideways during a panic stop. Using of antilock brake system, the driver can stop the vehicle in the shortest amount of time, and steering control fully maintains even if one or more wheels are on a slick road.

The basic components of an ABS involve an electronic control unit, a hydraulic actuator (scavenge pump), and wheel speed sensors. When the antilock brake system is out of order, basic brakes still function normally (Figure 27) (Ofria, 2000).

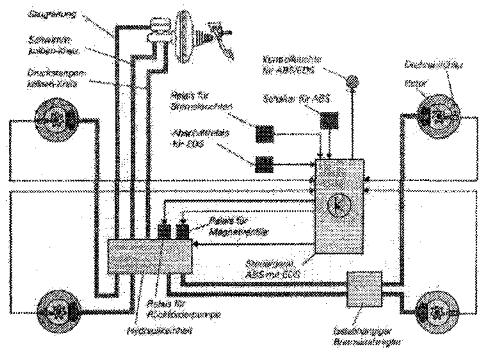


Figure 27 Priciple of ABS system (kfztech.de, 2006)

The original ABS was developed for heavy aircraft shortly after the Second World War. The Robert Bosch Corp invented the first modern automotive electronic ABS system, and it was offered on certain European Mercedes-Benz and BMW models in 1978. This day, more and more new vehicles are equipped with ABS as either standard or optional equipment (Carley and Mavrigian, 1998).

4.8 Vehicle Dynamics Control (VDC) Brake System

Vehicle Dynamics Control (VDC) system combines the basic functions of ABS with the unique ability to improve steering control and vehicle stability by braking any of the four vehicle wheels individually as needed to provide "corrective" steering. Thus, the VDC system utilizes the brakes to help straighten out a vehicle, whenever in danger of going out of control (Carley and Mavrigian, 1998).

A vehicle suddenly encounters a sharp right turn going too fast. The rear end begins to slide to the outside, which means the vehicle is in danger of losing control. If the driver hits the brakes, the rear wheels may lock up, which causes the car to get out of control, even if ABS is equipped. If the rear wheels are already starting to lose traction and slide outside, counter steering can not help either (Figure 28).

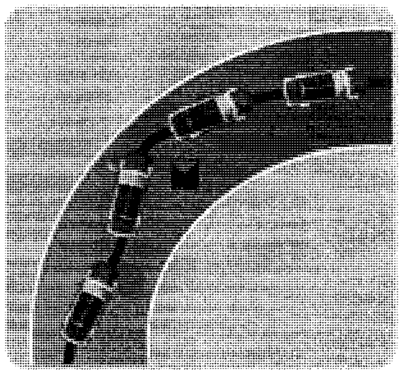


Figure 28 Vehicle running in a sharp turn (www.subaru.ch, 2006)

The VDC system would detect the problem as it begins to develop. Yaw rate sensor, the core of the VDC system, monitors any change in motion of the vehicle's vertical axis to detect under steer, over steer and fishtailing. A steering angle sensor mounted on the steering column detects the driver's steering inputs. So the VDC control module can receive information about which way the driver is steering the vehicle to judge if the vehicle is responding normally. By comparing wheel speeds obtained from wheel speed sensors with ideal ones, the control module can also determine if a normal speed differential exists between the inside and outside wheels when turning. The VDC control module compares all inputs from sensors to the default values saved in the program. If any of them fails to follow the VDC program maps, the control module determines that the vehicle is starting to lose its grip, and it helps to regain control in no time (Figure 29).

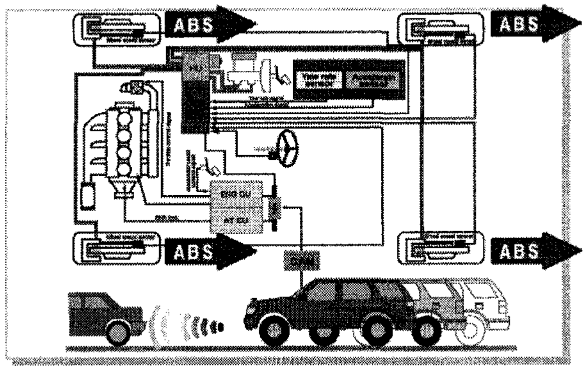


Figure 29 A typical VDC System (www.hitachi.co.jp, 1994)

ABS is only active when braking, but VDC serves all the time. The driver does not need to press the brake pedal, since VDC can detect the vehicle instability and react much more quickly than a human being. It helps stabilize and steer a vehicle by individual wheel braking at incredible speed, when adhesion of the vehicle is being pushed to the limits.

Vehicle Dynamics Control (VDC) is an invention of Robert Bosch Corp. It was first offered on 1996 Mercedes “s” class and E-420 modes. Nowadays, VDC system is equipped on more and more vehicles (Carley and Mavrigian, 1998).

4.9 Summary

From early mechanical brake system to vehicle dynamics control brake system, the vehicle brake system has experienced eight generations. Because human demands always keep increasing, the vehicle brake system became more and more complicated. Meanwhile, it tended to provide users with better and better functions (Table 2).

Evolution of Vehicle Brake Systems		
Product System	Invention Time	New Fuction
Eearly Mechanical Brake	1769	Brake the vehicle
External Band Brake	1895	Frictional device acted on a part other wheel tires
Internal Expanding Shoe Brake	1902	Wheather and dust proof
Hydraulic Brake	1920	Balance four-wheel braking
Power Brake	1930	Easy operation
Disc Brake	1898	Good cooling and water proof
Antilock Brake	1978	Avoid wheel lockup
Vehicle Dynamics Control Brake	1996	Maintain normal steering

Table 2 Evolution of vehicle brake systems

Chapter 5 Simulative Design of Early Mechanical Brake System

Environment-based Design Process is summarized as a systematic design model. Following this model, the simulative design of early mechanical brake system is made to validate EBD.

5.1 Summarization of Environment-based Design Process

We try to summarize Environment-based Design Process as a systematic design model, where the existing principles of EBD (Zeng and Cheng, 1991; Zeng and Gu, 1999a; Zeng, 2003; Zeng, 2004a; Zeng, 2004b; Chen and Zeng, 2006; Chen, Yao et al., 2007; Wang and Zeng, 2007b) are organized for solving a design problem.

(1) Environment-based Design Processes

The summarized Environment-based Design mainly comprises several steps as follows:

- ☐ Step 1: Map and analyze the original design problem
    - (1) Map the primitive description of design problem from the customer
    - (2) Draw the ROM diagram for the design problem
    - (3) Analyze the original design problem
- ☐ Step 2: Analyze the environment system
    - (1) Identify explicit environments
        - A. Find explicit environments

a. Product

b. Natural Environment

c. Built Environment

d. Human Environment

B. Search the relations between the environment components

a. Environment relation analysis

b. Clarification of unclear environments

- Questions to the customers or dictionaries etc.
- Answers from the customer and dictionary etc.

(2) Identify implicit environments

A. Find implicit environments

a. Design Event

b. Manufacture Event

c. Sales Event

d. Transportation Event

e. Use Event

f. Maintenance Event

g. Recycle Event

B. Update environments and draw a table of environments

C. Update the relations between all the environment components

a. Questions according to the relevant relations

b. Answers to the questions

- ☐ Step 3: Identify environment Conflicts (Driving Forces)

(1) Analyze the relations between environments

(2) Extract environment conflicts

- ☐ Step 4: Extract the Design requirements

(1) Extract the relevant design requirements according to the environment conflicts

(2) Analyze and evaluate the design requirements

A. Classification of design requirements obtained

B. Determine the priority of design requirements in terms of the eight levels

C. Evaluate feasibility of the design requirements

(3) Draw a table for all design requirements

(4) Draw the ROM diagram for design requirements

- ☐ Step 5: Generate design concepts

(1) Choose design requirements

(2) Create design sub-concepts

(3) Generate integral design concepts

- ☐ Step 6: Evaluate the design concepts

(1) Analyze the new environment system

(2) Identify new environment Conflicts

A. If acceptable, go to step 7

B. If not acceptable, go to step 2

- Step 7: Develop detailed Designs

(2) Method to Generate Design Concept

A design concept consists of some basic subsystems defined as design sub-concepts. In certain order and structure, these design sub-concepts are organized into an integral design concept. A design sub-concept should satisfy some design requirements or remove some environment conflicts. The ideas above can be expressed as follows.

$$D = \sum_{i=1}^{n} D_i \tag{15}$$

$$D_i = f(R_i) \tag{16}$$

$$D_i = f(C_i) \tag{17}$$

where D is the integral design concept, D_i is some design sub-concept, R_i is some design requirement, C_i is some environment conflict, and f is the solution to satisfy the design requirement or remove the environment conflict.

5.2 Simulative Design of Early Mechanical Brake System

This subsection will be simulative design of early mechanical brake system to validate EBD methodology.

5.2.1 Map and Analyze the Original Design Problem

(1) Map the preliminary description of design problem from the customer

Design Problem: To design a brake system for the new-designed motor vehicle.

(2) Draw the ROM diagram for the design problem (Figure 30)

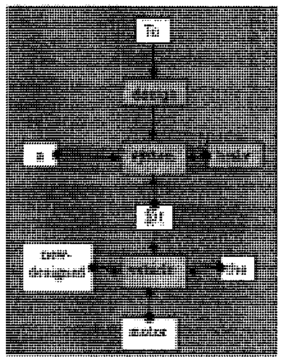


Figure 30 ROM diagram 1

(3) Analyze the original design problem

5.2.2 Analyze the Environment System

The environment of a product system can be classified into 3 types, namely, natural, built, and human environment (Zeng, 2004b).

Natural environment refers to all natural phenomena and natural laws related to a product in the product life cycle.

Built environment implies all man-made artefacts correlated to a product in the product life cycle.

Human environment means diverse people related to a product in the product life cycle. It includes designer, manufacturer, deliver, user, maintenance person, and so forth.

Sometimes the boundaries between the environments are not obvious. Also, such environments do not exist independently, but interact and influence mutually.

(1) Identify explicit environments

A. Find explicit environments

a. Natural environment: the earth, air, natural laws
b. Built environment: <u>the vehicle system without a brake system (wheels with steel rimmed tires, main vehicle body)</u>, the road
c. Human environment: <u>the user</u>

Please note: the whole vehicle is subjectively divided into two parts: the main vehicle body and wheels. The underlined environment components in this thesis indicate those directly related to the environment conflicts that cause design driving forces.

B. Search the relations between the environment components

a. Environment relation analysis

Air and Vehicle

The vehicle is surrounded by air, and the air drags the vehicle.

The Earth and Vehicle

The vehicle stays and runs on the earth, and the earth supports the vehicle.

Natural Laws and Other Environments

Gravitation

Under normal earth-bound conditions, when objects move owing to a constant gravitational force, a set of kinematical and dynamical equations describe the resultant trajectories. For example, Newton's law of gravitation simplifies to $F = mg$, where m is the mass of the body.

Energy Translation

Braking is the process slowing or stopping the motion of a vehicle. The velocity of the vehicle changes from high to low in a braking process, accompanying energy translation. The lost kinetic energy of the moving vehicle ($E = ½m \cdot v^2$, where m refers to the mass of the vehicle, v is the velocity of the vehicle) must be translated to other type of energy, when braking is applied.

Friction

The classical approximation of the force of friction known as Coulomb friction is expressed as: $F_f = \mu N$, where μ is the coefficient of friction, N is the normal force to the contact surface, and F_f is the maximum possible friction force.

Vehicle Brake System (VBS) and Vehicle

VBS is installed on the vehicle and becomes a part (subsystem) of the vehicle (super system)

Road and Vehicle

The vehicle runs on the road and the road upholds the vehicle (wheels).

Road and Wheel

Adhesive friction between a wheel and road most probably works as force factor of motion of the vehicle.

VBS and User (Driver)

The user (driver) will operate the VBS.

VBS and Manufacturer

The manufacturer will make the VBS.

b. Clarification of unclear environments

To make more clear sense of the product environment components and the relations, some questions should be asked and answered, as shown subsequently.

- Questions to customers or dictionaries

Q1: What motor vehicle without a brake system is designed?

Q2: Can you describe the structure of the motor vehicle?

Q3: What does "brake" mean?

- Answers from customers and dictionaries

A1: The vehicle with steel rim wheels is powered by a steam engine.

A2: The vehicle is shown in Figure 31.

A3: The brake system is used for slowing or stopping the motor vehicle.

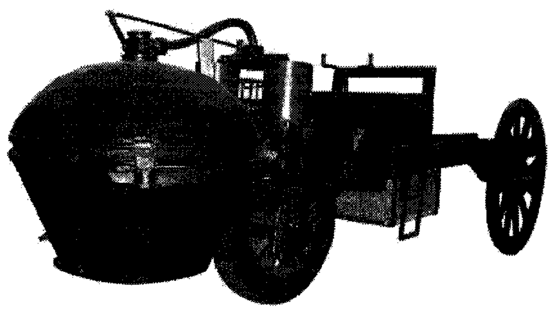


Figure 31 The new-designed motor vehicle (Joseph, 2006)

(2) Identify implicit environments

A. Find implicit environments

Implicit environment components could be found in terms of seven stages of the product cycle: design, manufacture, sales, transportation, use, maintenance, and recycle events. The design requirements relevant to product cycle events above are usually implicit environment components. At the beginning of the evolution of the motor vehicle, design work was exploring and tentative. The designers probably only focused on the following events: use event, manufacture event. So the considered implicit environments are:

a. The user

b. The manufacturer

B. Update environments and draw a table of environment system (Table 3)

Environment System of Early Mechanical Brake System		
Type	Environment Components	Number
Natural	the earth, air, natural laws (gravitation, friction, energy translation)	5
Built	vehicle (steel rimmed wheels, body, structure etc), road	4
Human	manufacturer, user	2

Table 3 Environment system of early mechanical brake system

C. Update the relations between all the environment components

a. Questions according to the relevant relations

Manufacture Event:

Q4: What is the manufacturing environment needed and provided for the new product?

Q5: What is the cost of making the brake system?

Use Event:

Q6: Who will be the users?

Q7: What is expected about the reliability and duality?

b. Answers to the questions

Manufacture Event:

A4: Workers will make the brake system under current technical condition.

A5: The cost of the brake system should be under corresponding budget.

Use Event:

A6: The driver will operate the brake system.

A7: Reliability and duality of the brake system should be acceptable.

5.2.3 Identify Environment Conflicts (Driving Forces)

Driving forces of design are conflicts between environment components of the product system (Zeng, 2004b).

When conflicts between environment components of a system occur, the whole system usually can not run properly any more. Then something new must be designed to remove the conflicts and then balance the system. So the criterion of a quality design is if the new design removes the conflicts and makes the relations between environment components harmonic.

(1) Analyze the Relations between Environments

To analyze the design driving forces of a vehicle brake system, how the vehicle system works should be well understood. A good way to do so is to analyze the relations between the environment components of the vehicle system. The dynamic analysis is a good sally port for the problem. Force is an influence that may cause a body to accelerate (change the current motion condition) (Newton's First Law). Actually, force is a reciprocal relation between interactional environment components of a system.

Next, the dynamic analysis of the vehicle system without brakes in deceleration will be made. We will analyze the dynamics of the vehicle wheels, the main body, and the whole vehicle respectively (Yu, 1990). The dynamic analysis diagrams will first be drawn to help further calculate the deceleration value of the vehicle. To simplify the problem, it assumes that the vehicle stays or runs forward on a straight horizontal road.

A. Dynamic Analysis Diagrams of the Vehicle System without Brakes

The dynamic analysis diagrams is to identify the dynamic relations of vehicle system without brakes in deceleration to lay a foundation for further mathematic analysis (Yu, 1990).

a. For the Vehicle Wheels

If the driving torque from the driving axle drops to certain value, negative unbalanced resultant forces exert on moving vehicle wheels. Then the wheels are in motion of deceleration. Both the linear velocity and angular velocity of the wheels are greater than zero, and the linear acceleration and angular acceleration are less than zero ($Vv>0$, $\omega>0$, $dv/dt<0$, and $d\omega/dt<0$) (Figure 32).

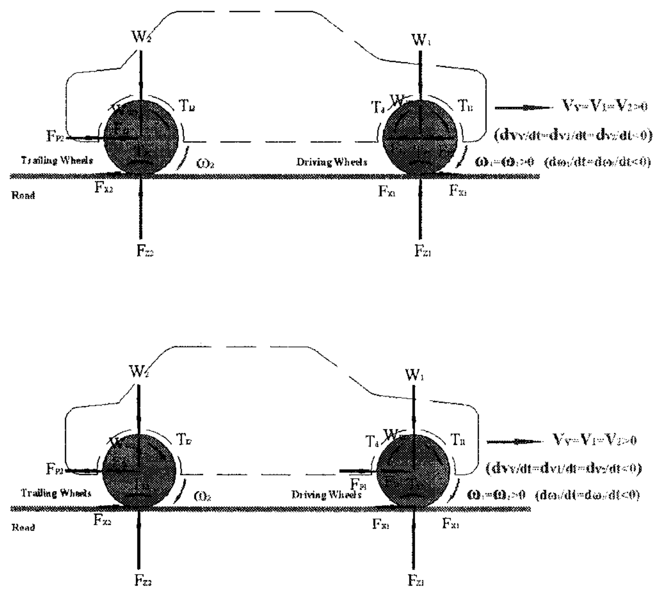


Figure 32 Dynamic analysis of wheels in deceleration

where V is linear velocity, V_V is the linear velocity of the vehicle, V_1 is the linear velocity of the driving wheels, V_2 is the linear velocity of the trailing wheels, ω is angular velocity, ω_1 is the angular velocity of the driving wheels, ω_2 is the angular velocity of the trailing wheels, r is the radius of the wheels, F_{I1} is the inertia force of the driving wheels, m_1 is mass of the driving wheels, $\frac{dV_1}{dt}$ is the linear acceleration of the driving wheels, T_{I1} is the inertia couple of the driving wheels, I_1 is the moment of inertia of driving wheels, $\frac{d\omega_1}{dt}$ is the angular acceleration of the driving wheels, F_{p1} is the pressure component along the road applied to the driving wheels by the main vehicle body, F_{X1} is the friction applied to the driving wheels by road, F_{Z1} is the normal force applied to the driving wheels by road, T_{F1} is the rolling resistance moment applied to the driving wheels by the road, T_D is the driving torque applied to the driving wheels by the driving axle, F_D is the driving force applied to the driving wheels by the driving axle, F_{I2} is the inertia force of the trailing wheels, m_2 is mass of the trailing wheels, $\frac{dV_2}{dt}$ is the linear acceleration of the trailing wheels, T_{I2} is the inertia couple of the trailing wheels, I_2 is the moment of inertia of trailing wheels, $\frac{d\omega_2}{dt}$ is the angular acceleration of the trailing wheels, F_{p2} is the pressure component along the road applied to the trailing wheels by dead axle, F_{X2} is the friction applied to the trailing wheels by road, F_{Z2} is the normal force applied to the trailing wheels by road, T_{F2} is the rolling resistance moment applied to trailing wheels by the road, F_{F2} is the rolling resistance applied to the driving wheels by the road, and a is the distance between F_Z and vertical line passing the center of the wheels.

Please note: the dynamic condition in deceleration motion depends on the amount of driving torque applied on the driving wheels. From the uniform motion, as the driving torque decrease, F_{P1} decreases from original value to zero, and then to certain negative value (change of the direction). Meanwhile, F_{P2} keeps on decreasing until certain value, but does not change the direction.

b. For the Main Vehicle Body

If negative unbalanced resultant force is exerted on the moving main vehicle body, it should be in motion of deceleration. The linear velocity of the main vehicle body is greater than zero, and the linear acceleration is less than zero (Vv>0, ω>0, dv/dt<0, and dω/dt<0) (Figure 33).

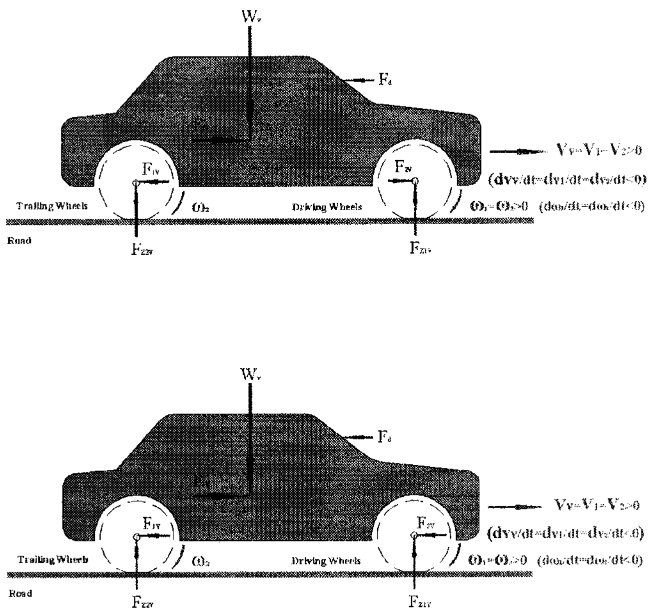


Figure 33 Dynamic analysis of vehicle body in deceleration

where F_{1V} is the force applied to the main vehicle body by the driving wheels, F_{2V} is the force applied to the main vehicle body by the trailing wheels, m_V is mass of the main vehicle body, $\frac{dV_V}{dt}$ is the linear acceleration of the main vehicle body.

c. For the Whole Vehicle System

When the whole vehicle system (super system) is considered an integrated object of study, forces between the subsystems are not considered. If a negative unbalanced resultant force is exerted on the whole moving vehicle system, it should be in motion of acceleration. The linear velocity of the whole vehicle is greater than zero, and the linear acceleration is less than zero (Vv>0 and dv/dt<0) (Figure 34).

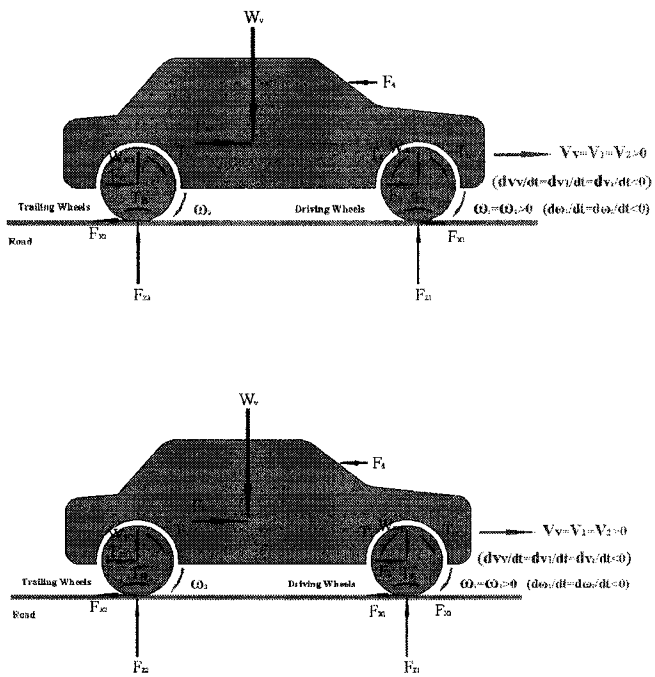


Figure 34 Dynamic analysis of the whole vehicle in deceleration

B. Deceleration Value of the Vehicle System without Brakes

The calculation of deceleration value of the vehicle system without brakes can help to find the environment conflicts.

a. For the Vehicle Wheels

Some basic equations related to the vehicle system can be obtained as follows (Yu, 1990).

$$V = V_V = V_1 = V_2 = V_i \tag{18}$$

$$\frac{dV}{dt} = \frac{dV_V}{dt} = \frac{dV_1}{dt} = \frac{dV_2}{dt} = \frac{dV_i}{dt} \quad (19)$$

$$V = \omega \cdot r \quad (20)$$

$$\omega = \omega_1 = \omega_2 = \omega_i \quad (21)$$

$$\frac{d\omega}{dt} = \frac{d\omega_1}{dt} = \frac{d\omega_2}{dt} = \frac{d\omega_i}{dt} \quad (22)$$

Driving Wheels

$$F_{I1} = m_1 \cdot \frac{dV_1}{dt}$$

$$T_{I1} = I_1 \cdot \frac{d\omega_1}{dt}$$

$$F_{X1} = F_{P1} + F_{I1}$$

$$F_{X1} = F_{P1} + m_1 \cdot \frac{dV_1}{dt}$$

$$T_{F1} = F_{Z1} \cdot a$$

$$F_{F1} = T_{F1} / r$$

$$F_{X1} \cdot r = T_D - T_{I1} - T_{F1}$$

$$F_D = T_D / r$$

$$F_D = F_{P1} + F_{Z1}\frac{a}{r} + (m_1 + \frac{I_1}{r^2}) \cdot \frac{dV_1}{dt} \tag{23}$$

Tailing Wheels

$$F_{I2} = m_2 \cdot \frac{dV_2}{dt}$$

$$T_{I2} = I_2 \cdot \frac{d\omega_2}{dt}$$

$$F_{P2} = F_{I2} + F_{X2}$$

$$F_{P2} = m_2 \cdot \frac{dV_2}{dt} + F_{X2}$$

$$T_{F2} = F_{Z2} \cdot a$$

$$F_{F2} = T_{F2} / r$$

$$F_{X2} \cdot r = T_{F2} + T_{I2}$$

$$F_{P2} = F_{Z2}\frac{a}{r} + (m_2 + \frac{I_2}{r^2}) \cdot \frac{dV_2}{dt} \tag{24}$$

b. For the Main Vehicle Body

$$F_{P1} = F_{1V}$$

$$F_{P2} = F_{2V}$$

$$m_v \cdot \frac{dV_v}{dt} = F_{1V} - F_{2V}$$

$$m_v \frac{dV_v}{dt} = F_{P1} - F_{P2}$$

$$F_{P1} = F_{P2} + m_v \cdot \frac{dV_v}{dt} \tag{25}$$

c. For the Whole Vehicle System

From equation (18), (19), (20), (23), (24) and (25), we can derive the following results.

$$\frac{dV}{dt} = \left[(F_D - (F_{Z2} \frac{a}{r} + F_{Z1} \frac{a}{r}) \right] / \left[(m_2 + \frac{I_2}{r^2}) + m_v + (m_1 + \frac{I_1}{r^2}) \right] \tag{26}$$

When $\frac{dV}{dt} < 0$, the vehicle is in decelerated motion. To obtain the maximum deceleration magnitude, let $F_D = 0$ (no driving torque).

$$\frac{dV}{dt} = \left[-(F_{Z2} \frac{a}{r} + F_{Z1} \frac{a}{r}) \right] / \left[(m_2 + \frac{I_2}{r^2}) + m_v + (m_1 + \frac{I_1}{r^2}) \right]$$

$$\frac{dV}{dt} = \left[-(F_{Z2} + F_{Z1}) \frac{a}{r} \right] / \left[(m_2 + \frac{I_2}{r^2}) + m_v + (m_1 + \frac{I_1}{r^2}) \right]$$

$$F_{Z2} + F_{Z1} = (m_2 + m_v + m_1) g$$

$$f = \frac{a}{r}$$

$$\frac{dV}{dt} = \left[-(m_2 + m_v + m_1)\cdot g \cdot f\right] / \left[(m_2 + \frac{I_2}{r^2}) + m_v + (m_1 + \frac{I_1}{r^2})\right] \tag{27}$$

$$\frac{dV}{dt} > -\left[(m_2 + m_v + m_1)\cdot g \cdot f\right]/(m_2 + m_v + m_1) = -g \cdot f \tag{28}$$

We can draw a conclusion from inequation (25) that, a running vehicle without driving and braking should be in deceleration ($\frac{dV}{dt}$<0), and the deceleration magnitude ($\left|\frac{dV}{dt}\right|$) is less than $g \cdot f$.

For a steel-rimmed wheel, f values should be much smaller than those for a pneumatic rubber tire wheel (typically 0.01-0.05). We set f a value 0.01, and a deceleration magnitude ($\left|\frac{dV}{dt}\right|$) bigger than the actual can be obtained as follows.

$$\frac{dV}{dt} > -g \cdot f = -0.01 * 9.8 = -0.098 \cdot m/s^2$$

(2) Extract Environment Conflicts

On the one hand, the vehicle sometimes needs to stop quickly as the driver expects, when running on road. They wish the stopping distance was close to zero.

On the other hand, the actual deceleration magnitude that the existing vehicle system without a brake system can provide, should be less than $0.098 \cdot m/s^2$. Then the stopping distance can be calculated as follows.

$$S = V_0 * t + \frac{1}{2}at^2 \tag{29}$$

$$t = V_0 / a \tag{30}$$

V_0= 5m/s and a=−0.098

S=125m

where S is the stopping distance, V_0 is the vehicle initial velocity, a is the vehicle deceleration, and t is the stopping time.

Obviously, the stopping distance is too long, or such a deceleration magnitude is too small to stop the vehicle rapidly. A satisfactory deceleration can not be obtained, which means the existing vehicle system have no way to provide sufficient drag force for braking as the driver requires. As a result, the driving force of design of the early mechanical brake system is the conflicts between the existing vehicle system and the driver: the existing heavy vehicle system with steam engine can not be stopped or slowed down easily and rapidly as the driver desires.

More detailed environment conflicts can be found by further analysis so as to help extract design requirements in the future.

- The driver has no way to <u>stop the vehicle</u> quickly enough.
- The driver has no way to stop<u> the heavy vehicle with steam engine</u>.
- The driver has no way to stop the vehicle when driving <u>on the vehicle</u>.
- The driver has no way to <u>operate easily</u> to stop the vehicle.

Then, something new, a special subsystem-brake system, has to be designed to balance the conflicts, and consequently satisfy the driver's need for slowing down the vehicle quickly.

5.2.4 Extract the Design Requirements

Before the expected product design arises, there exist conflicts, because human being's requirements can be not satisfied by the current environment that they live. Only after the new design arises, can the environment conflicts be removed and can design requirements be satisfied. Design requirements directly or indirectly come from environment conflicts. Design requirements can be extracted by studying the environment conflicts and other resource.

(1) Extract the Design Requirements

A. Extract Design Requirements from Environment Conflicts

R1: The main basic function of the brake system is to slow down and stop the motor vehicle.

R2: A sufficient powerful brake system is needed for such a powerful vehicle.

R3: The brake system should have reasonable structure and layout in order to match the vehicle structure.

R4: The driver will operate the brake system conveniently.

B. Extract More Design Requirements from other Environment Relations

R5: Workers will make the brake system under current technical condition.

R6: The cost of the brake system should be under corresponding budget.

R7: Reliability and duality of the brake system should be acceptable.

C. Draw Table of Design Requirements (Table 4)

Design Requirements of Early Mechanical Brake System	
Design Requirements	R1: The main basic function of the brake system is to slow down and stop the motor vehicle. R2: A sufficient powerful brake system is needed for such a powerful vehicle. R3: The brake system should have reasonable structure and layout in order to match the vehicle structure. R4 The driver will operate the brake system conveniently. R5: Workers will make the brake system under current technical condition. R6: The cost of the brake system should be under corresponding budget. R7: Reliability and duality of the brake system should be acceptable.

Table 4 Design requirements of early mechanical brake system

D. Draw ROM Diagram of Design Requirements (Figure 35)

Some design requirements may be expressed by different words so as to conveniently draw ROM diagrams.

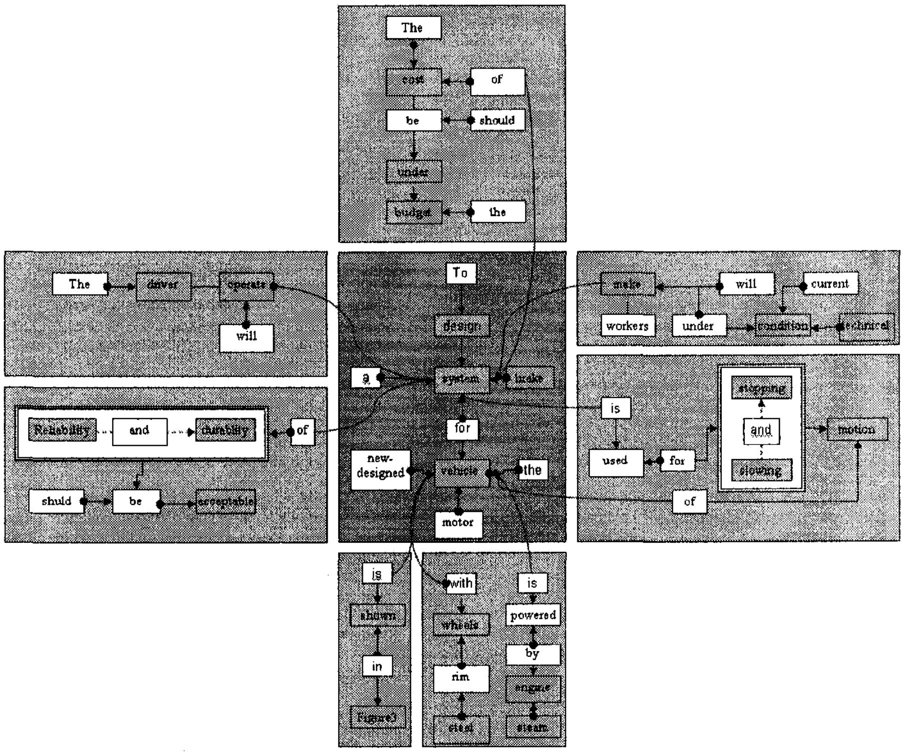


Figure 35 ROM diagram 2

(2) Analyze the design requirements

The analysis of design requirements will be made by classifying in terms of events of product cycle and prioritizing in terms of the eight levels.

R1: The main basic function of the brake system is to slow down and stop the motor vehicle.

Use Event + Basic functions level

R2: A sufficient powerful brake system is needed for such a powerful vehicle.

Use Event + Basic functions level

R3: The brake system should have reasonable structure and layout in order to match the vehicle structure.

Design event +Natural laws and rules

R4: The driver will operate the brake system conveniently.

Use Event + Hunan-machine interface level

R5: Workers will make the brake system under current technical condition.

Manufacture Event + Social laws, technical regulations or other mandatory criteria level

R6: The cost of the brake system should be under corresponding budget.

Sales Event + Cost, time and human resource level

R7: Reliability and duality of the brake system should be acceptable.

Use Event + Basic Functions or Extended Functions

(3) Evaluate the Design Requirements

All these basic design requirements should be satisfied in the future design.

5.2.5 Generate Design Concepts

This concept design of early mechanical brake system only focuses on structure design, while other aspects are not discussed here.

(1) Choose Design Requirements

R_1: The main basic function of the brake system is to slow down and stop the motor vehicle.

R_2: The driver will operate the brake system conveniently.

R_3: The brake system should have reasonable structure and layout in order to match the vehicle structure.

(2) Create Design Sub-concepts

$D_1=f(R_1)$: Frictional devices are needed to decelerate the vehicle fast enough.

$D_2=f(R_2)$: A convenient brake operation system is needed.

$D_3=f(R_3)$: The brake structure and layout should match the vehicle structure and layout.

(3) Generate Integral Design Concept

In certain order and structure, the design sub-concepts obtained above are organized into an integral design concept of early mechanical brake system. The structure representation is drawn as below (Figure 36).

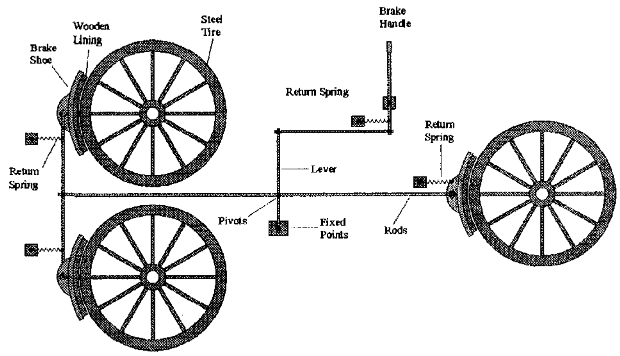


Figure 36 Structure of early mechanical brake system

5.2.6 Evaluate Design Concepts

(1) Analyze the New Environment System

A. Identify the New Environment System

a. Natural environment: the earth, air, natural laws

b. Built environment: the vehicle system (wheels with steel rimmed tires, main vehicle body, early mechanical brake system), the road

c. Human environment: the user, the manufacturer

B. Search the Relations between the Environment Components

Because new components join the environment system, some new environment relations arise.

Brake System and Vehicle

The brake system acts on the vehicle wheels to brake the vehicle.

Driver and Brake System

The driver operates the brake system to brake the vehicle.

(2) Identify New Environment Conflicts

We now investigate the environment conflicts of the vehicle system with the early mechanical brake system when braking by dynamic analysis.

A. Dynamic Analysis Diagrams of the New Vehicle When Braking

The drawing below shows dynamic conditions of the new vehicle system when braking (Figure 37). As the driving torque exerted on the driving wheels changes, the dynamic conditions vary correspondingly.

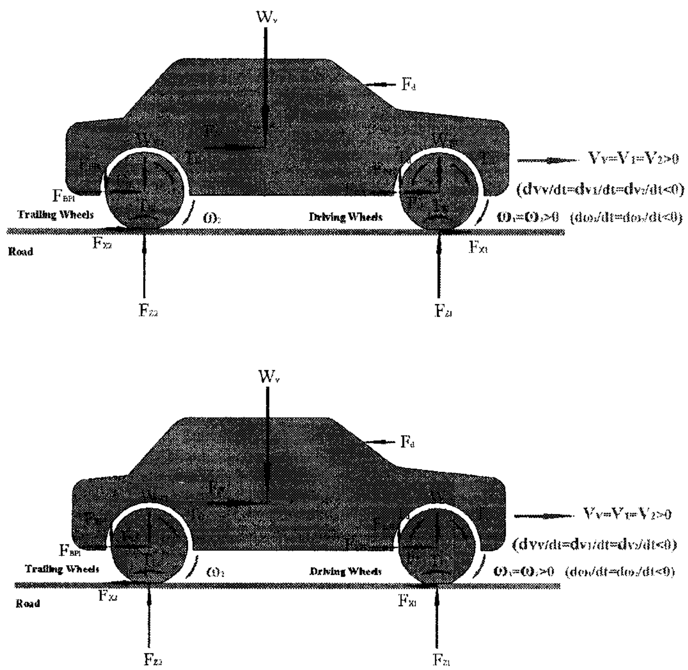


Figure 37 Dynamic analysis of the new vehicle system when braking

where F_{BP1} is the pressure applied to the driving wheels by brakes, F_{BF1} is the friction force applied to the driving wheels by brakes, F_{BP2} is the pressure applied to the trailing wheels by brakes, F_{BF2} is the friction force applied to the trailing wheels by brakes, and μ is the friction coefficient between the trailing wheels and brakes.

Moreover, the dynamic analysis of the early mechanical brake can be seen in Figure 38. Assuming that no driving torque is applied, all wheels are in same dynamic condition.

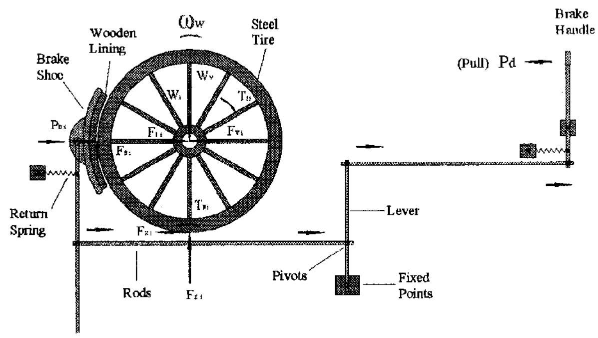


Figure 38 Dynamic analysis of early mechanical brake system

B. Deceleration Value of the New Vehicle System When Braking

a. For the Vehicle Wheels

Driving Wheels

$$F_{I1} = m_1 \cdot \frac{dV_1}{dt}$$

$$T_{I1} = I_1 \cdot \frac{d\omega_1}{dt}$$

$$F_{X1} + F_{BP1} = F_{P1} + F_{I1}$$

$$T_{F1} = F_{Z1} \cdot a$$

$$F_{F1} = T_{F1} / r$$

$$F_{X1} \cdot r = T_D - T_{I1} - T_{F1} - T_{B1}$$

$$F_D = T_D / r$$

$$T_{B1} = F_{BF1} \cdot r$$

$$F_{BF1} = \mu_B \cdot F_{BP1}$$

$$F_{P1} - F_{BP1} = F_D - (m_1 + \frac{I_1}{r^2}) \cdot \frac{dV_1}{dt} - F_{Z1} \frac{a}{r} - \mu \cdot F_{BP1} \tag{31}$$

Trailing Wheels

$$F_{I2} = m_2 \cdot \frac{dV_2}{dt}$$

$$T_{I2} = I_2 \cdot \frac{d\omega_2}{dt}$$

$$F_{P2} + F_{BP2} = F_{I2} + F_{X2}$$

$$F_{X2} \cdot r = T_{F2} + T_{I2} + T_{B2}$$

$$T_{B2} = F_{BF2} \cdot r$$

$$F_{BF2} = \mu \cdot F_{BP2}$$

$$T_{F2} = F_{Z2} \cdot a$$

$$F_{F2} = T_{F2} / r$$

$$F_{P2} = F_{Z2} \frac{a}{r} + (m_2 + \frac{I_2}{r^2}) \cdot \frac{dV_2}{dt} + \mu \cdot F_{BP2} - F_{BP2} \tag{32}$$

b. For the Main Vehicle Body

$$F_{P1} = F_{1V}$$

$$F_{P2} = F_{2V}$$

$$m_v \cdot \frac{dV_v}{dt} = F_{1V} - F_{2V}$$

$$m_v \frac{dV_v}{dt} = F_{P1} - F_{P2} - F_{BP1} - F_{BP2} \tag{33}$$

c. For the Whole Vehicle System

From equation 18, 19, 31, 32, and 33, we can derive the following results.

$$\frac{dV_B}{dt} = (F_D - F_{Z1} \frac{a}{r} - \mu \cdot F_{BP1} - F_{Z2} \frac{a}{r} - \mu_B \cdot F_{BP2}) / \left[(m_2 + \frac{I_2}{r^2}) + (m_1 + \frac{I_1}{r^2}) + m_v \right] \tag{34}$$

To obtain the maximum deceleration magnitude, let $F_D = 0$ (no driving torque).

$$\frac{dV_B}{dt} = -\left[(F_{Z1} + F_{Z2})\frac{a}{r} + \mu \cdot (F_{BP1} + F_{BP2})\right] / \left[(m_2 + \frac{I_2}{r^2}) + (m_1 + \frac{I_1}{r^2}) + m_v\right] \quad (35)$$

where $\frac{dV_B}{dt}$ is the linear acceleration of the vehicle when braking.

Now we can compare the two deceleration values by finding their difference:

$$\frac{dV_B}{dt} - \frac{dV}{dt} = -[\mu \cdot (F_{BP1} + F_{BP2})] / \left[(m_2 + \frac{I_2}{r^2}) + (m_1 + \frac{I_1}{r^2}) + m_v\right] \quad (36)$$

C. Search Environment Conflicts

With the action of the early mechanical brake system, the horizontal frictions F_X and friction torques T_f applied on the wheels can increase dramatically. As a result, provided the driver exert enough pull on the brake handle, the heavy vehicle system with steam engine can get sufficient deceleration ($\frac{dV_B}{dt}$) to stop or slow down quickly as the driver desires. So the previous environment conflict was removed, and no unacceptable conflict exists any more.

(3) Evaluate the Design Concept

As the early mechanical brake system can greatly increase the deceleration and stop or slow down the vehicle rapidly, the pervious environment conflicts are removed and the new vehicle system is in balance. Consequently, the design concept is considered qualified.

5.3 Summary

Environment-based Design can provide designers with a well-organized design model, and proved to be an effective tool to formalize design process. It was comprehensively applied and verified in the simulative design of early mechanical brake system.

Driving forces of design are conflicts between different environment components of the product system (Zeng, 2004b). Actually, such conflicts are contradictions between human environment components (human being) and other environment components. Specifically, they embody in the gap between increasing human needs and functions of existing product systems. Then something new (new product) has to be designed to remove the conflicts and balance the system.

Design requirements directly or indirectly come from the conflicts between environment components. Design requirements can be obtained by analyzing the relations between product environments. After the design requirements are analyzed, classified, some of the most important are selected and considered for subsequent design work.

A design concept consists of some basic subsystems named design sub-concepts. In certain order and structure, these design sub-concepts are organized into an integral design concept. A design sub-concept should satisfy some design requirements or remove some environment conflicts. The integral design concept should integrally remove the environment conflicts (design driving forces), and satisfy design requirements.

Chapter 6 Analysis of Vehicle Brake System Evolution

The evolution of design solutions is an important part of study of design methods. We turn to research brake systems in terms of evolution, so as to find the laws or trends how a product develops. We expect to provide designers with some enlightenment for their future work. The research will be developed from three aspects: environment analysis and conflict identification, design requirement extraction and analysis, and concept generation and evaluation. Considering that a detailed simulative design of early mechanical brake system was already done in Chapter 5, we only discuss relevant aspects of the rest brake systems here.

6.1 Environment Analysis and Conflict Identification

The driving force of design is an influence to motivate people to make a new design. Zeng proposed that driving forces of design are conflicts between environment components of a product system (Zeng, 2004b). Environment analysis can help find design driving forces.

6.1.1 External Band Brake System

(1) Identify Environment System

Natural environment: the earth, air, natural laws

Built environment: road, the vehicle system (wheels with the pneumatic rubber tires, main body, structure, early mechanical brake system)

Human environment: designer, manufacturer, salesman, transporter, user, maintenance man, recycle man

The product environments are shown in Table 5.

Environment System of External Band Brake System		
Type	Environment Components	Number
Natural	the earth, air, natural laws (gravitation, friction, energy translation)	5
Built	vehicle (pneumatic rubber tires, body, structure etc), road, early mechanical brake system	5
Human	designer, manufacturer, salesman, transporter, user, maintenance man, recycle man	7

Table 5 Environments of external band brake system

(2) Analyze Environment Conflicts (Design Driving Forces)

The driving force of design of external band brake system is the conflicts between the early mechanical brake system, the wheels with the pneumatic rubber tires, and the driver: the early mechanical brake system can not well match the pneumatic rubber tires due to the poor wear property. The service lives of those tires are not as satisfying as desired, if the early mechanical brake system continues to be used. A new brake system is expected to replace the early mechanical brake system.

6.1.2 Internal Expanding Shoe Brake System

(1) Identify Environment System

Natural environment: the earth, air, natural laws, weather (rain, snow-water), dust

Built environment: road, the vehicle system (wheels with the pneumatic rubber tires, main body, structure, external band brake system)

Human environment: designer, manufacturer, salesman, transporter, user, maintenance man, recycle man

The product environments are shown in Table 6.

Environment System of Internal Expanding Shoe Brake System		
Type	Environment Components	Number
Natural	the earth, air, natural laws (gravitation, friction, energy translation), Weathering (rain, snow), dust	8
Built	vehicle (pneumatic rubber tires, body, structure etc), road, external band brake system	5
Human	designer, manufacturer, salesman, transporter, user, maintenance man, recycle man	7

Table 6 Environments of internal expanding shoe brake system

(2) Analyze Environment Conflicts (Design Driving Forces)

The driving force of design of internal expanding shoe brake system is the conflicts between the external band brake system, weathering (rain and snow), road dirt, and the driver: the external band brake system is not weatherproof and dustproof due to its open structure. Then it has problems in loss of efficiency, rapid wear of lining, and occasionally "automatic" braking application. But the driver desires to avoid all theses problems. A new brake system is expected to replace the external band brake system.

6.1.3 Hydraulic Brake System

(1) Identify Environment System

Natural environment: the earth, air, natural laws, weather (rain, snow-water), dust

Built environment: road, the vehicle system (wheels with the pneumatic rubber tires, main body, structure, internal expanding shoe brake system (mechanical operation system, actuator (brake shoe, drum)

Human environment: designer, manufacturer, salesman, transporter, user, maintenance man, recycle man

The product environments are shown in Table 7.

Environment System of Hydraulic Brake System		
Type	Environment Components	Number
Natural	the earth, air, natural laws (gravitation, friction, energy translation), Weathering (rain, snow), dust	8
Built	vehicle (pneumatic rubber tires, body, structure etc), road, internal expanding shoe brake system (brake operation system, actuators)	7
Human	designer, manufacturer, salesman, transporter, user, maintenance man, recycle man	7

Table 7 Environments of hydraulic brake system

(2) Analyze Environment Conflicts (Design Driving Forces)

The driving force of design of the hydraulic brake system is the conflicts between the internal expanding shoe brake system (mechanical operation system -a linkage system of fixed rods and levers supplement by Bowden cables, actuator (brake shoe, drum) and the driver: the internal expanding shoe brake system has trouble in keeping in good operating order for the linkage system of rods and levers, and equalizing brake pressure on the wheels, which the driver desires to avoid. A new brake system is expected to replace the internal expanding shoe brake system.

6.1.4 Power Brake System

(1) Identify Environment System

Natural environment: the earth, air, natural laws, weather (rain, snow-water), dust

Built environment: road, the vehicle system (wheels with the pneumatic rubber tires, main body, structure, hydraulic brake system), operating conformability

Human environment: designer, manufacturer, salesman, transporter, user, maintenance man, recycle man

The product environments are shown in Table 8.

Environment System of Power Brake System		
Type	Environment Components	Number
Natural	the earth, air, natural laws (gravitation, friction, energy translation), Weathering (rain, snow), dust	8
Built	vehicle (pneumatic rubber tires, body, structure etc), road, hydraulic brake system (Brake operation system, actuators), operating conformability	8
Human	designer, manufacturer, salesman, transporter, user, maintenance man, recycle man	7

Table 8 Environments of power brake system

(2) Analyze Environment Conflicts (Design Driving Forces)

The driving force of design of the power brake system is the conflicts between the hydraulic brake system ((hydraulic operation system, actuator (brake shoe, drum)) and the driver: the hydraulic brake system can not be operated as easily as the driver desires. A new brake system is expected to replace the hydraulic brake system.

6.1.5 Disc Brake System

(1) Identify Environment System

Natural environment: the earth, air, natural laws, weather (rain, snow-water), dust, heat dissipating, paddle

Built environment: road, the vehicle system (wheels with the pneumatic rubber tires, main body, structure, power brake system), operating conformability

Human environment: designer, manufacturer, salesman, transporter, user, maintenance man, recycle man

The product environments are shown in Table 9.

Environment System of Disc Brake System		
Type	Environment Components	Number
Natural	the earth, air, natural laws (gravitation, friction, energy translation), Weathering (rain, snow), dust, heat dissipating, paddle	10
Built	vehicle (pneumatic rubber tires, body, structure etc), road, power brake system (Brake operation system, actuators), operating conformability	8
Human	designer, manufacturer, salesman, transporter, user, maintenance man, recycle man	7

Table 9 Environments of disc brake system

(2) Analyze Environment Conflicts (Design Driving Forces)

The driving force of design of the disc brake system is the conflicts between the existing drum brake system (brake shoe, drum), heat generated by braking, water and the driver: the drum brake system not only has trouble in cooling well, but also traps water, which the driver desires to avoid. A new brake system is expected to replace the power brake system.

6.1.6 Antilock Brake System (ABS)

(1) Identify Environment System

Natural environment: the earth, air, natural laws, weather (rain, snow-water), dust heat dissipating, paddle

Built environment: road, the vehicle system (wheels with the pneumatic rubber tires, main body, structure, disc brake system), operating conformability, braking efficiency, steering control

Human environment: designer, manufacturer, salesman, transporter, user, maintenance man, recycle man

The product environments are shown in Table 10.

Environment System of Antilock Brake System		
Type	Environment Components	Number
Natural	the earth, air, natural laws (gravitation, friction, energy translation), Weathering (rain, snow), dust, heat dissipating, paddle	10
Built	vehicle (pneumatic rubber tires, body, structure etc), road, Disc brake system (Brake operation system, actuators), operating conformability, braking efficiency, steering control	10
Human	designer, manufacturer, salesman, transporter, user, maintenance man, recycle man	7

Table 10 Environments of antilock brake system

(2) Analyze Environment Conflicts (Design Driving Forces)

The driving force of design of the antilock brake system is the conflicts between the existing brake system, brake efficiency, steering control and the driver: the existing brake system has trouble in providing efficient brake force and keeping steering control when wheels lock up, which the driver desires to avoid. A new brake system is expected to replace the disc brake system.

6.1.7 Vehicle Dynamics Control (VDC) Brake System

(1) Identify Environment System

Natural environment: the earth, air, natural laws, weather (rain, snow-water), dust heat dissipating, paddle

Built environment: road, the vehicle system (wheels with the pneumatic rubber tires, main body, structure, antilock brake system), operating conformability, braking efficiency, steering control, sharp turn road

Human environment: designer, manufacturer, salesman, transporter, user, maintenance man, recycle man

The product environments are shown in Table 11.

Environment Components of Vehicle Dynamics Control Brake System		
Type	Environment Components	Number
Natural	the earth, air, natural laws (gravitation, friction, energy translation), Weathering (rain, snow), dust, heat dissipating, paddle	10
Built	vehicle (pneumatic rubber tires, body, structure etc), road, Antilock brake system (Brake operation system, actuators), operating conformability, braking efficiency, steering control, Sharp turn road	11
Human	designer, manufacturer, salesman, transporter, user, maintenance man, recycle man	7

Table 11 Environments of dynamics control brake system

(2) Analyze Environment Conflicts (Design Driving Forces)

The driving force of design of the vehicle dynamics control brake system (VDC) is the conflicts between the existing anti-lock brake system (ABS) the vehicle (stability), sharp turn road and the driver: the existing anti-lock brake system (ABS) has trouble in vehicle stability control when the vehicle enters a sharp turn fast, which the driver desires to avoid. A new brake system is expected to replace the anti-lock brake system.

6.2 Design Requirement Extraction and Analysis

Any brake system evolved and improved from its predecessor. Every brake system usually needs to satisfy most design requirements of all precedent brake systems. To avoid unnecessary repetition, only new design requirements will be listed correspondingly. But the tables and ROM diagrams include all the relevant design requirements to illustrate the progressive evolution clearly.

6.2.1 External Band Brake System

(1) New Design Requirements

R8. The design should strictly follow relevant technical and safety standards.

Design event + Social laws, technical regulations or other mandatory criteria level

R9. The brake system should be easy for normal delivery and transportation.

Transportation Event + Extended function level.

R10. The design of the brake system should follow ergonomics.

Use Event + Hunan-machine interface level

R11. The brake system should be easy to replace, repair and install.

Maintenance Event + Extended function level.

R12. The brake system could be recycled conveniently.

Recycle + Event + Extended function level.

(2) Draw Table of Design Requirements (Table 12)

Design Requirements of External Band Brake System	
	R1: The main basic function of the brake system is to slow down and stop the motor vehicle.
	R2: A sufficient powerful brake system is needed for such a powerful vehicle.
	R3: The brake system should have reasonable structure and layout in order to match the vehicle structure.
Design	R4 The driver will operate the brake system conveniently.
	R5: Workers will make the brake system under current technical condition.
	R6: The cost of the brake system should be under corresponding budget.
	R7: Reliability and duality of the brake system should be acceptable.
Requirements	R8. The design should strictly follow relevant technical and safety standards.
	R9. The brake system should be easy for normal delivery and transportation.
	R10. The design of the brake system should follow ergonomics.
	R11. The brake system should be easy to replace, repair and install.
	R12. The brake system could be recycled conveniently.

Table 12 Design requirements of external band brake system

(3) Draw ROM Diagram of Design Requirements (Figure 39)

To conveniently draw the ROM diagrams, some of design requirements may be rewritten.

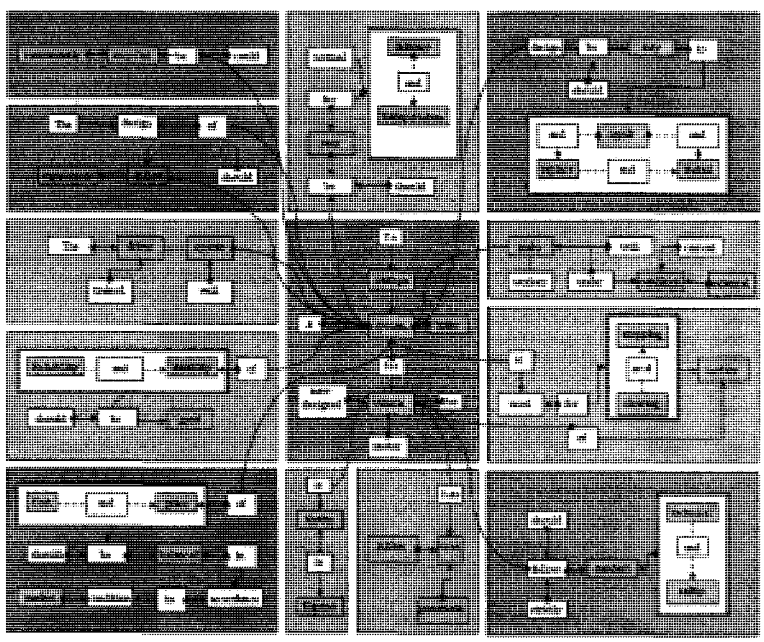


Figure 39 ROM diagram 3

6.2.2 Internal Expanding Shoe Brake System

(1) New Design Requirements

R13. The brake system should be protected from weather and dust.

Design event + Extended function

(2) Draw Table of Design Requirements (Table 13)

Design Requirements of Internal Expanding Shoe Brake System	
Design Requirements	R1: The main basic function of the brake system is to slow down and stop the motor vehicle.
	R2: A sufficient powerful brake system is needed for such a powerful vehicle.
	R3: The brake system should have reasonable structure and layout in order to match the vehicle structure.
	R4 The driver will operate the brake system conveniently.
	R5: Workers will make the brake system under current technical condition.
	R6: The cost of the brake system should be under corresponding budget.
	R7: Reliability and duality of the brake system should be acceptable.
	R8. The design should strictly follow relevant technical and safety standards.
	R9. The brake system should be easy for normal delivery and transportation.
	R10. The design of the brake system should follow ergonomics.
	R11. The brake system should be easy to replace, repair and install.
	R12. The brake system could be recycled conveniently.
	R13: The brake system should be protected from weather and dust.

Table 13 Design requirements of internal expanding shoe brake system

(3) Draw ROM Diagram of Design Requirements (Figure 40)

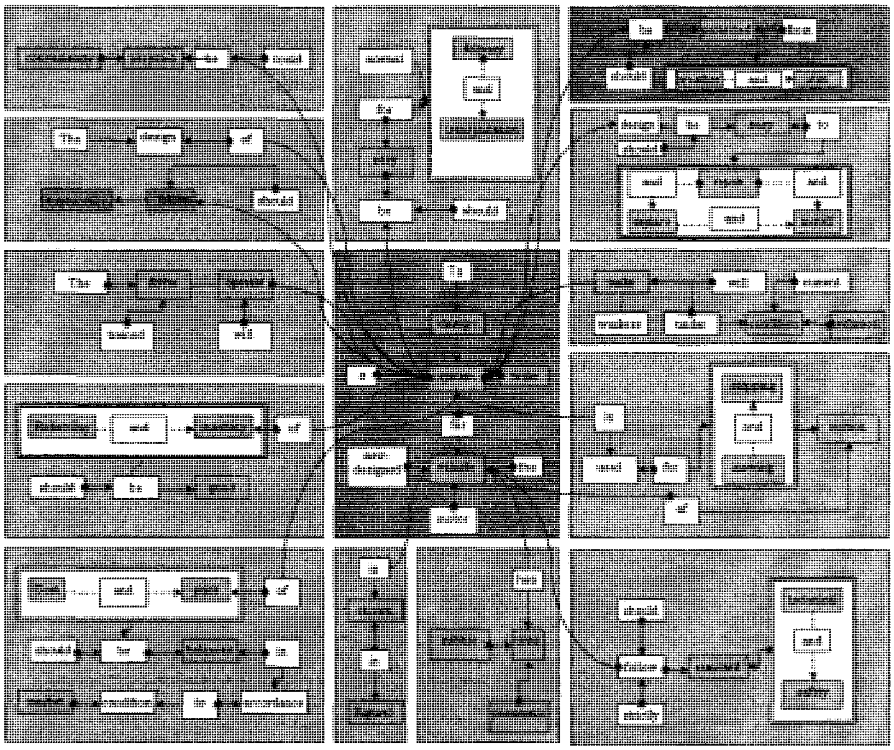


Figure 40 ROM diagram 4

6.2.3 Hydraulic Brake System

(1) New Design Requirements

R14. The operation system of the new brake system should be easy to keep in good operating order.

Use Event + Basic Functions or Extended Functions

R15. The operation system of the new brake system should be easy to equalize brake pressure on all wheels.

Use Event + Basic Functions or Extended Functions

(2) Draw Table of Design Requirements (Table 14)

Design Requirements of Hydraulic Brake System	
Design Requirements	R1: The main basic function of the brake system is to slow down and stop the motor vehicle.
	R2: A sufficient powerful brake system is needed for such a powerful vehicle.
	R3: The brake system should have reasonable structure and layout in order to match the vehicle structure.
	R4 The driver will operate the brake system conveniently.
	R5: Workers will make the brake system under current technical condition.
	R6: The cost of the brake system should be under corresponding budget.
	R7: Reliability and duality of the brake system should be acceptable.
	R8. The design should strictly follow relevant technical and safety standards.
	R9. The brake system should be easy for normal delivery and transportation.
	R10. The design of the brake system should follow ergonomics.
	R11. The brake system should be easy to replace, repair and install.
	R12. The brake system could be recycled conveniently.
	R13: The brake system should be protected from weather and dust.
	R14. The operation system of the new brake system should be easy to keep in good operating order.
	R15. The operation system of the new brake system should be easy to equalize brake pressure on all wheels.

Table 14 Design requirements of hydraulic brake system

(3) Draw ROM Diagram of Design Requirements (Figure 41)

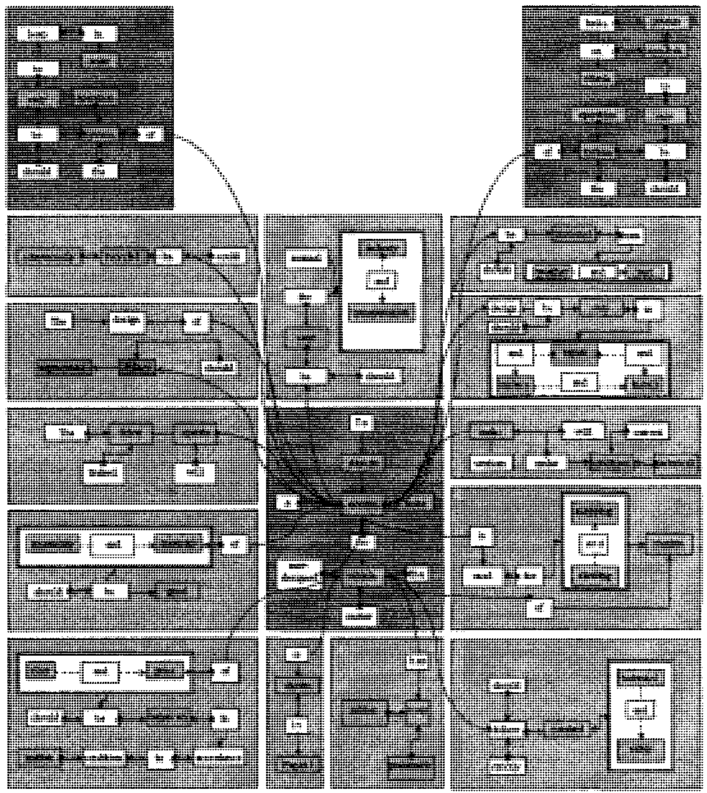


Figure 41 ROM diagram 5

6.2.4 Power Brake System

(1) New Design Requirements

R16. The brake system should be power-assisted to reduce the amount of force required to pull the lever or press on the pedal in order to stop the vehicle.

Use Event + Basic functions level

(2) Draw Table of Design Requirements (Table 15)

Design Requirements of Power Brake System	
Design Requirements	R1: The main basic function of the brake system is to slow down and stop the motor vehicle.
	R2: A sufficient powerful brake system is needed for such a powerful vehicle.
	R3: The brake system should have reasonable structure and layout in order to match the vehicle structure.
	R4 The driver will operate the brake system conveniently.
	R5: Workers will make the brake system under current technical condition.
	R6: The cost of the brake system should be under corresponding budget.
	R7: Reliability and duality of the brake system should be acceptable.
	R8. The design should strictly follow relevant technical and safety standards.
	R9. The brake system should be easy for normal delivery and transportation.
	R10. The design of the brake system should follow ergonomics.
	R11. The brake system should be easy to replace, repair and install.
	R12. The brake system could be recycled conveniently.
	R13: The brake system should be protected from weather and dust.
	R14. The operation system of the new brake system should be easy to keep in good operating order.
	R15. The operation system of the new brake system should be easy to equalize brake pressure on all wheels.
	R16. The brake system should be power-assisted to reduce the amount of force required to pull the lever or press on the pedal in order to stop the vehicle.

Table 15 Design requirements of power brake system

(3) Draw ROM Diagram of Design Requirements (Figure 42)

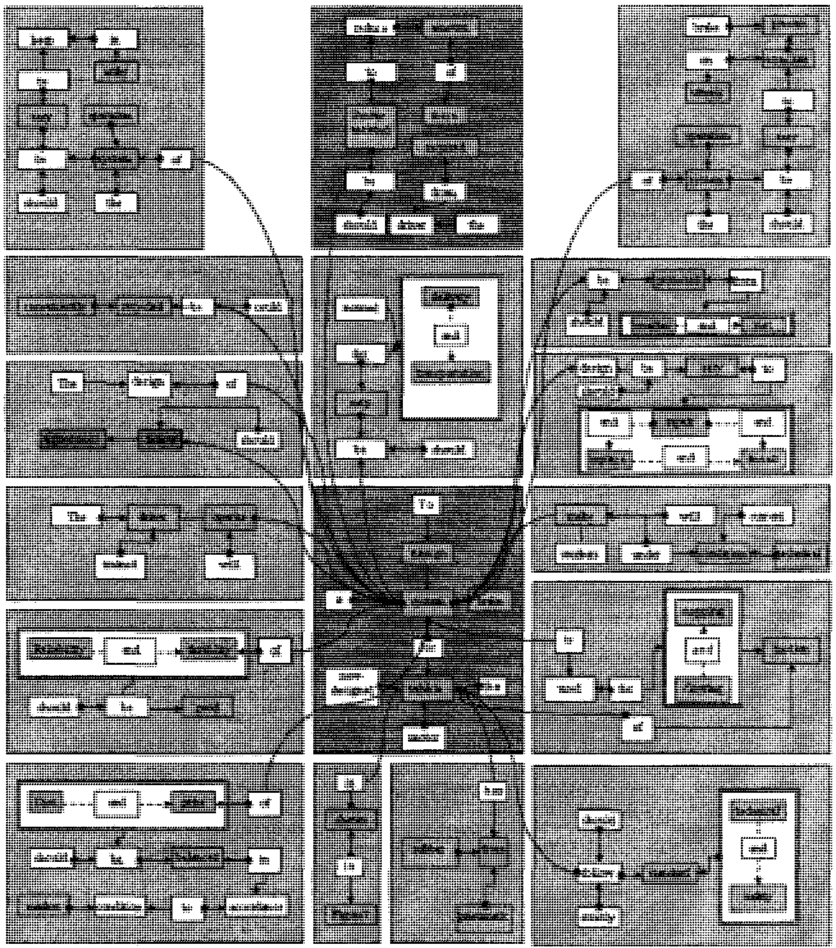


Figure 42 ROM diagram 6

6.2.5 Disc Brake System

(1) New Design Requirements

R17. The brake system should have better ability to dissipate heat.

Use Event + Basic Functions or Extended Functions

R18. The brake system can not trap abrasive dust and water.

Use Event + Basic Functions or Extended Functions

(2) Draw Table of Design Requirements (Table 16)

Design Requirements of Disc Brake System	
Design Requirements	R1: The main basic function of the brake system is to slow down and stop the motor vehicle.
	R2: A sufficient powerful brake system is needed for such a powerful vehicle.
	R3: The brake system should have reasonable structure and layout in order to match the vehicle structure.
	R4 The driver will operate the brake system conveniently.
	R5: Workers will make the brake system under current technical condition.
	R6: The cost of the brake system should be under corresponding budget.
	R7: Reliability and duality of the brake system should be acceptable.
	R8. The design should strictly follow relevant technical and safety standards.
	R9. The brake system should be easy for normal delivery and transportation.
	R10. The design of the brake system should follow ergonomics.
	R11. The brake system should be easy to replace, repair and install.
	R12. The brake system could be recycled conveniently.
	R13: The brake system should be protected from weather and dust.
	R14. The operation system of the new brake system should be easy to keep in good operating order.
	R15. The operation system of the new brake system should be easy to equalize brake pressure on all wheels.
	R16. The brake system should be power-assisted to reduce the amount of force required to pull the lever or press on the pedal in order to stop the vehicle.
	R17. The brake system should have better ability to dissipate heat.
	R18. The brake system can not trap abrasive dust and water.

Table 16 Design requirements of disc brake system

(3) Draw ROM Diagram of Design Requirements (Figure 43)

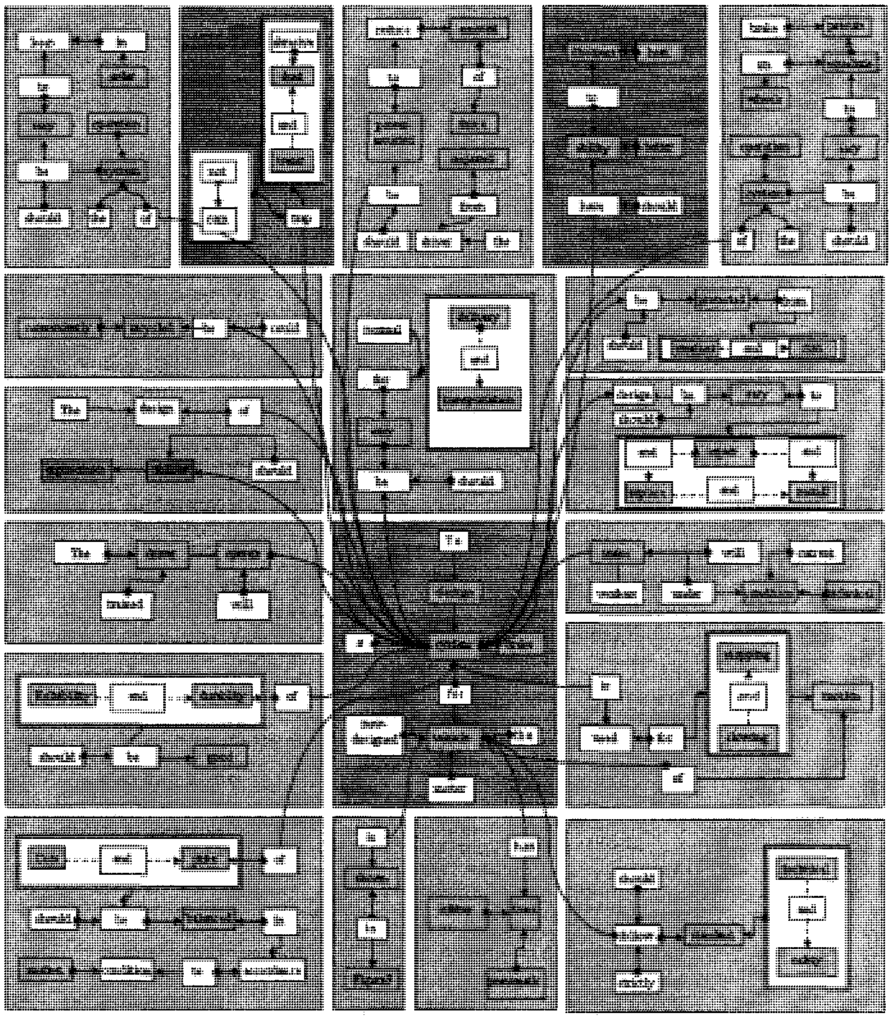


Figure 43 ROM diagram 7

6.2.6 Antilock Brake System (ABS)

(1) New Design Requirements

R19. The wheels should not lock up any time when braking.

Use Event + Basic Functions or Extended Functions

(2) Draw Table of Design Requirements (Table 17)

Design Requirements of Antilock Brake System	
Design Requirements	R1: The main basic function of the brake system is to slow down and stop the motor vehicle.
	R2: A sufficient powerful brake system is needed for such a powerful vehicle.
	R3: The brake system should have reasonable structure and layout in order to match the vehicle structure.
	R4 The driver will operate the brake system conveniently.
	R5: Workers will make the brake system under current technical condition.
	R6: The cost of the brake system should be under corresponding budget.
	R7: Reliability and duality of the brake system should be acceptable.
	R8. The design should strictly follow relevant technical and safety standards.
	R9. The brake system should be easy for normal delivery and transportation.
	R10. The design of the brake system should follow ergonomics.
	R11. The brake system should be easy to replace, repair and install.
	R12. The brake system could be recycled conveniently.
	R13: The brake system should be protected from weather and dust.
	R14. The operation system of the new brake system should be easy to keep in good operating order.
	R15. The operation system of the new brake system should be easy to equalize brake pressure on all wheels.
	R16. The brake system should be power-assisted to reduce the amount of force required to pull the lever or press on the pedal in order to stop the vehicle.
	R17. The brake system should have better ability to dissipate heat.
	R18. The brake system can not trap abrasive dust and water.
	R19. The wheels should not lock up any time when braking.

Table 17 Design requirements of antilock brake system

(3) Draw ROM Diagram of Design Requirements (Figure 44)

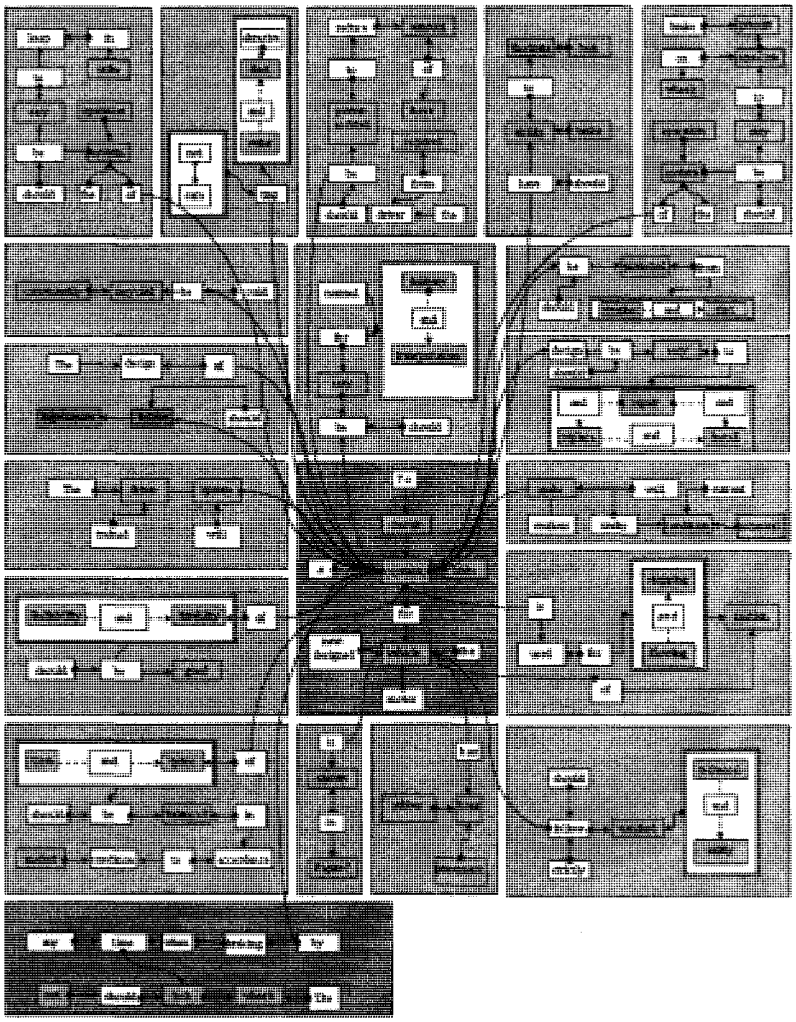


Figure 44 ROM diagram 8

6.2.7 Vehicle Dynamics Control (VDC) Brake System

(1) New Design Requirements

R20. The brake system should help the vehicle keep stable.

Use Event + Basic Functions or Extended Functions

(2) Draw Table of Design Requirements (Table 18)

Design Requirements of Vehicle Dynamics Control Brake System	
Design Requirements	R1: The main basic function of the brake system is to slow down and stop the motor vehicle. R2: A sufficient powerful brake system is needed for such a powerful vehicle. R3: The brake system should have reasonable structure and layout in order to match the vehicle structure. R4 The driver will operate the brake system conveniently. R5: Workers will make the brake system under current technical condition. R6: The cost of the brake system should be under corresponding budget. R7: Reliability and duality of the brake system should be acceptable. R8. The design should strictly follow relevant technical and safety standards. R9. The brake system should be easy for normal delivery and transportation. R10. The design of the brake system should follow ergonomics. R11. The brake system should be easy to replace, repair and install. R12. The brake system could be recycled conveniently. R13: The brake system should be protected from weather and dust. R14. The operation system of the new brake system should be easy to keep in good operating order. R15. The operation system of the new brake system should be easy to equalize brake pressure on all wheels. R16. The brake system should be power-assisted to reduce the amount of force required to pull the lever or press on the pedal in order to stop the vehicle. R17. The brake system should have better ability to dissipate heat. R18. The brake system can not trap abrasive dust and water. R19. The wheels should not lock up any time when braking. R20. The brake system should help the vehicle keep stable.

Table 18 Design requirements of vehicle dynamics control brake system

(3) Draw ROM Diagram of Design Requirements (Figure 45)

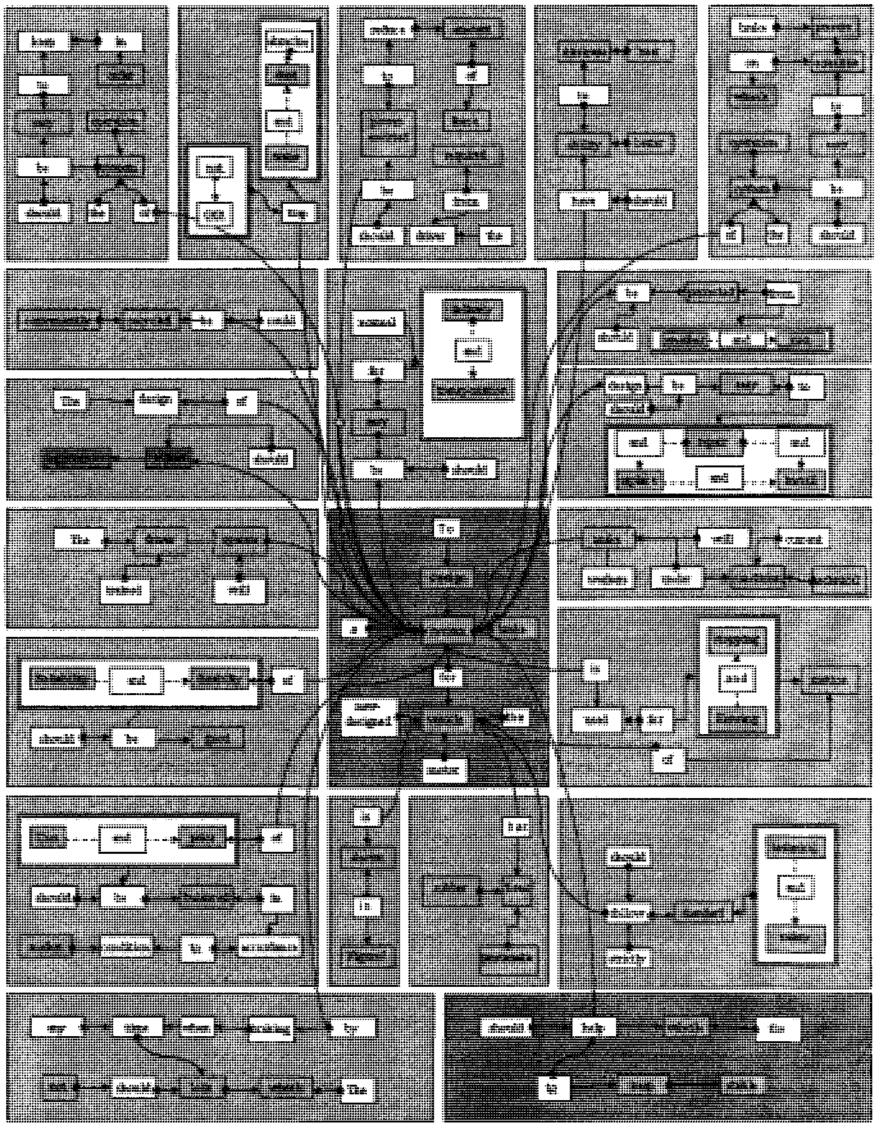


Figure 45 ROM diagram 9

6.3 Concept Generation and Evaluation

As a critical step of a design process, concept design is to generate general ideas or conceptions of a product. We will get help from concept generations and evaluations of vehicle brake systems to study the discipline of product evolution.

6.3.1 External Band Brake System

(1) Generate Design Concept

Based on the design requirements obtained, a design concept of external band brake system can be made. The structure representation is illustrated as follows (Figure 46).

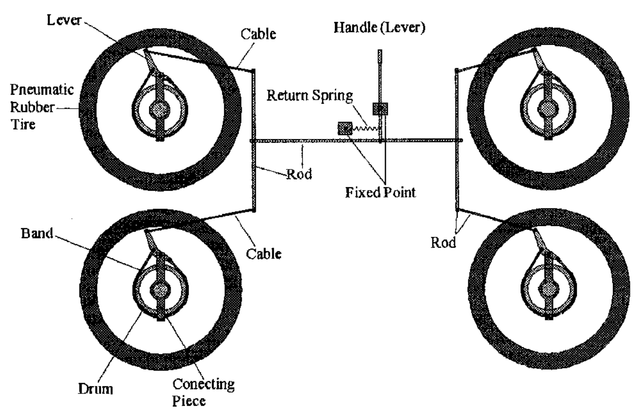


Figure 46 Structure of external band brake system

(2) Evaluate Design Concept

The frictional bands of external band brake system act on outsides of the drums (parts other than wheel tires) to brake the vehicle. The design removes relevant environment conflicts (design driving forces). Its working principle is shown in Figure 47.

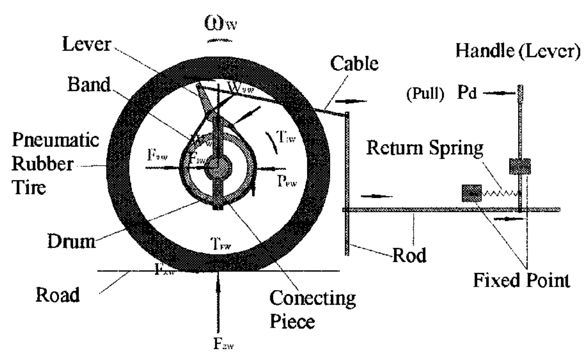


Figure 47 Dynamic analysis of external band brake system

6.3.2 Internal Expanding Shoe Brake System

(1) Generate Design Concept

Based on the design requirements obtained, a design concept of internal expanding shoe brake system can be made. The structure representation is illustrated as follows (Figure 48).

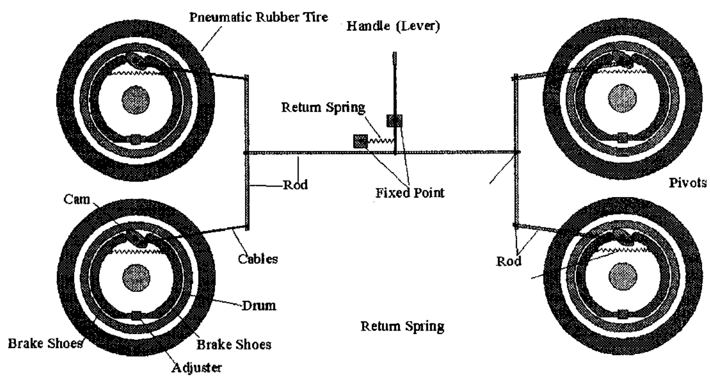


Figure 48 Structure of internal expanding shoe brake system

(2) Evaluate Design Concept

The internal expanding shoe brake system has enclosed structure, where brake shoes act on insides of the drums to brake the vehicle. The design removes relevant environment conflicts (design driving forces). Its working principle is shown in Figure 49.

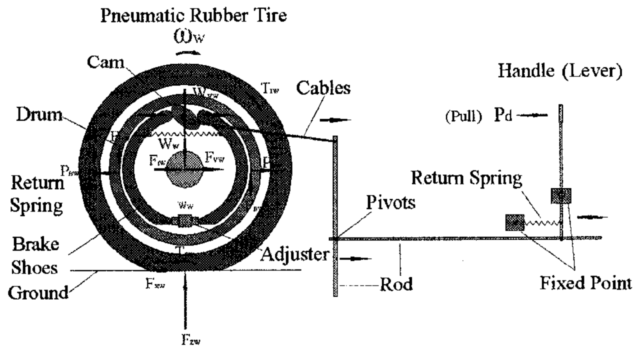


Figure 49 Dynamic analysis of internal expanding shoe brake system

6.3.3 Hydraulic Brake System

(1) Generate Design Concept

Based on the design requirements obtained, a design concept of hydraulic brake system can be made. The structure representation is illustrated as follows (Figure 50).

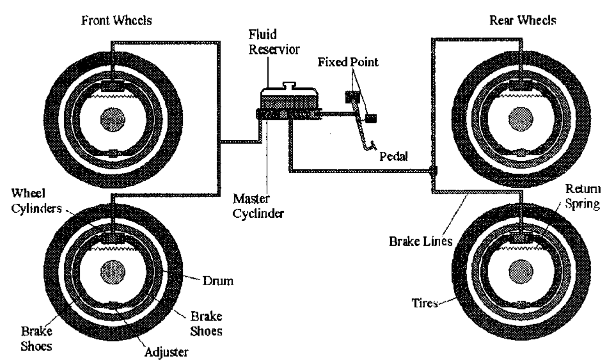


Figure 50 Structure of hydraulic brake System

(2) Evaluate Design Concept

The hydraulic brake system provides balanced four-wheel braking, since the pressure is transmitted from the master cylinder to the pistons of each wheel cylinders equally without weakening and time lag. The design removes relevant environment conflicts (design driving forces). Its working principle is shown in Figure 51.

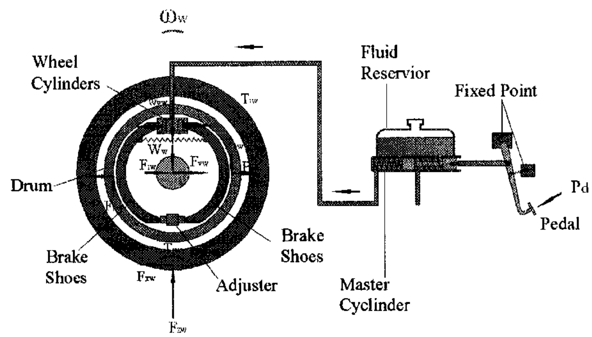


Figure 51 Dynamic analysis of hydraulic brake System

6.3.5 Power Brake System

(1) Generate Design Concept

Based on the design requirements obtained, a design concept of power brake system can be made. The structure representation is illustrated as follows (Figure 52).

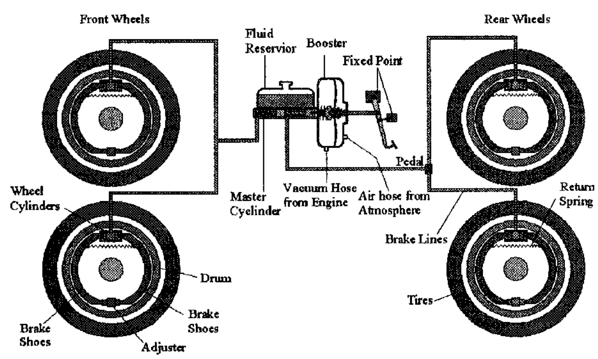


Figure 52 Structure of power brake System

(3) Evaluate Design Concept

Power brakes use a boosters and usually engine vacuum or hydraulic pressure to assist brake pedal application. The design removes relevant environment conflicts (design driving forces). Its working principle is shown in Figure 53.

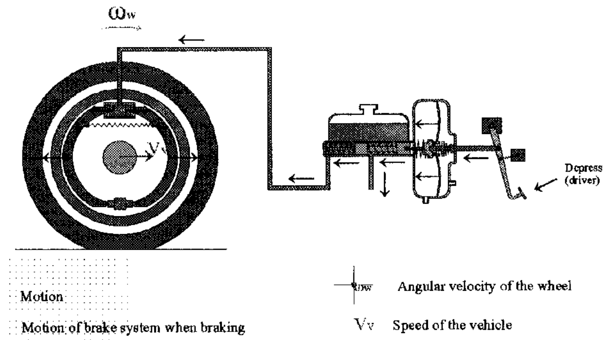


Figure 53 Dynamic analysis of power brake System

6.3.6 Disc Brake System

(1) Generate Design Concept

Based on the design requirements obtained, a design concept of disc brake system can be made. The structure representation is illustrated as follows (Figure 54, 55, 56).

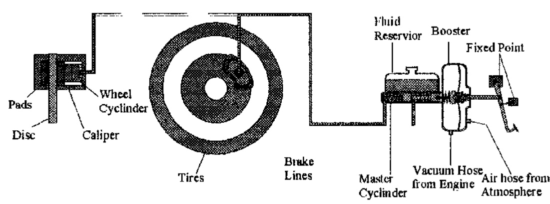


Figure 54 Structure of disc brake system 1

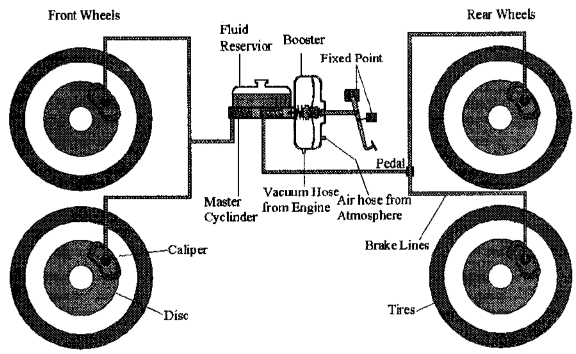


Figure 55 Structure of disc brake system 2

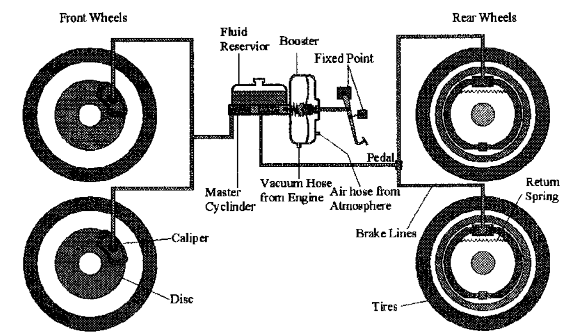


Figure 56 Structure of disc brake system 3

(2) Evaluate Design Concept

Compared with drum brakes, disc brakes have many advantages. First, disc brakes have sufficient cooling ability. The exposed flat faces and the addition of fins and vents between the faces of the rotor guarantee its good ability to dissipate heat. Second, the open structure makes them not trap water again, which provides a safe design for wet weather driving. Third, self-adjusting ability of disc brakes simplifies the design by eliminating self adjusters or periodic adjustment. The design removes relevant environment conflicts (design driving forces). Its working principle is shown in Figure 57.

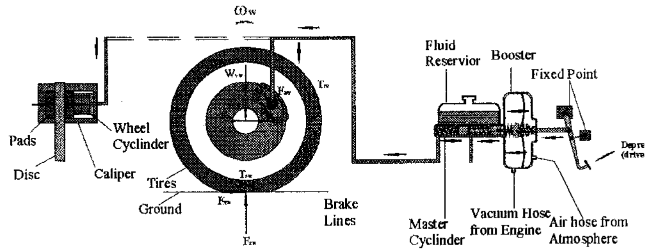


Figure 57 Dynamic analysis of disc brake system

6.3.7 Antilock Brake System (ABS)

(1) Generate Design Concept

Based on the design requirements obtained, a design concept of antilock brake system can be made. The structure representation is illustrated as follows (Figure 58).

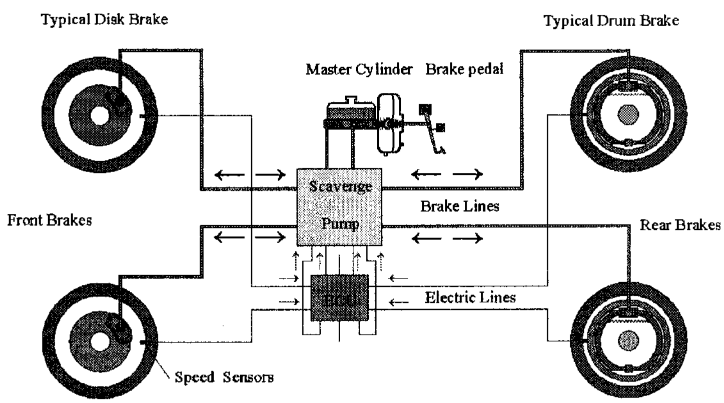


Figure 58 Structure antilock brake system (ABS)

(2) Evaluate Design Concept

ABS helps avoid wheel lockup by rapidly pumping the brakes whenever the system detects that any of wheels is becoming locked up. The design removes relevant environment conflicts (design driving forces). Its working principle is also shown in Figure 58.

6.3.8 Vehicle Dynamics Control (VDC) Brake System

(1) Generate Design Concept

Based on the design requirements obtained, a design concept of Vehicle Dynamics Control brake system can be made. The structure representation is illustrated as follows (Figure 59).

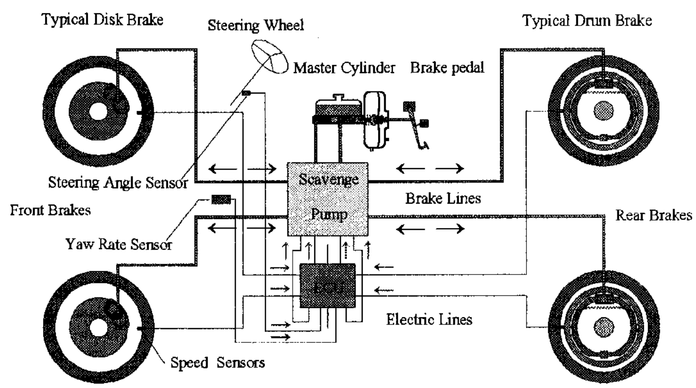


Figure 59 Structure of vehicle dynamics control brake system

(2) Evaluate Design Concept

Vehicle Dynamics Control system combines the basic functions of ABS with the unique ability to improve steering control and vehicle stability by braking any of the four vehicle wheels individually as needed to provide "corrective" steering. Thus, the VDC system utilizes the brakes to help straighten out a vehicle, whenever in danger of going out of control. The design removes relevant environment conflicts (design driving forces). Its working principle is also shown in Figure 59.

6.4 Summary

Laws or trends about how a product system develops were studied by analyzing the evolution of brake systems.

Change of environment is the immanent cause of product evolution. Change takes place daily, and nothing remains the same. Product environments keep changing all the time. These changes sometimes can result in environment conflicts or make it probable to remove existing environment conflicts. The advent of pneumatic rubber tires brought conflict between them and early mechanical brake system, which was the design driving force for external band brake system. The discovery of Pascal's law laid a foundation of invention of hydraulic brake system.

A new product system usually evolves and improves from its predecessors. The new product system trends to involve more and more product environments (Table 19, Figure 60, 61). It often needs to satisfy most design requirements of all precedent product systems (Table 20, Figure 62, 63). Designers have to consider new environment components to search new design requirements in the design processes.

Vehicle Brake System Designs	Number of Environment Components			
	Natrual	Built	Hunam	Total
Early Mechanical Brake System	5	4	2	11
External Band Brake System	5	5	7	17
Internal Expanding Shoe Brake System	8	5	7	20
Hydraulic Brake System	8	7	7	22
Power Brake System	8	8	7	23
Disc Brake System	10	8	7	25
Antilock Brake System	10	10	7	27
Vehicle Dynamics Control Brake System	10	11	7	28

Table 19 Environment numbers of vehicle brake systems

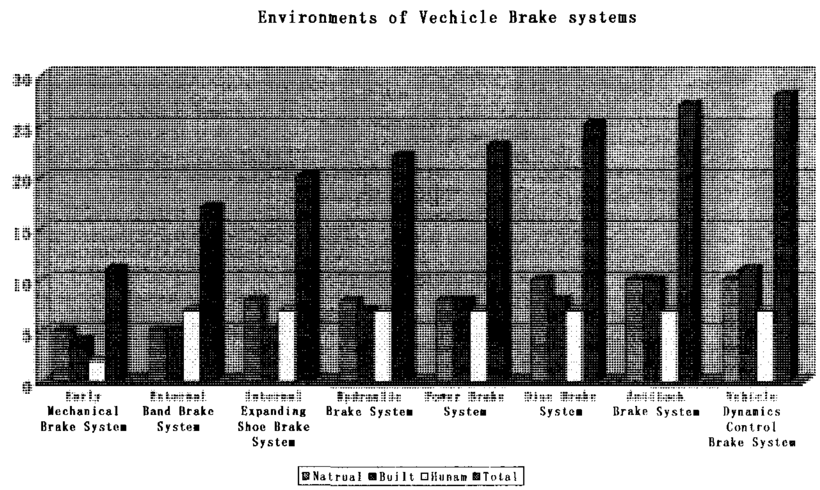


Figure 60 Environment numbers of vehicle brake systems 1

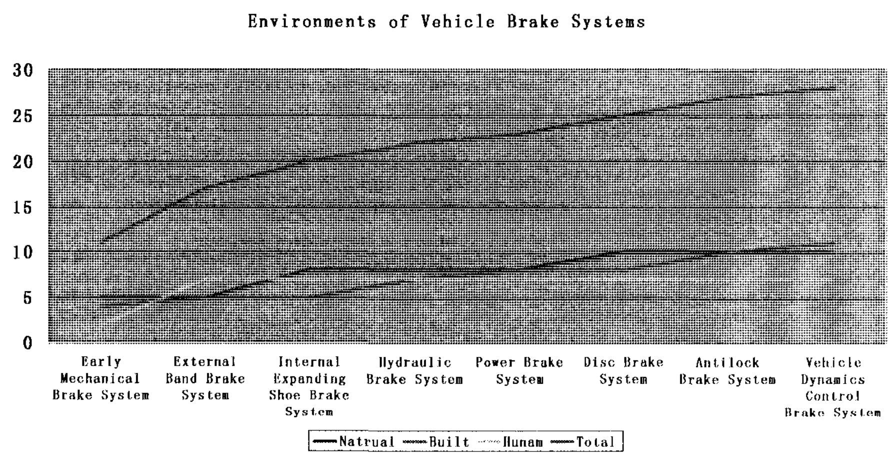


Figure 61 Environment numbers of vehicle brake systems 2

Vehicle Brake System Designs	Number of Design Requirements
Early Mechanical Brake System	7
External Band Brake System	12
Internal Expanding Shoe Brake System	13
Hydraulic Brake System	15
Power Brake System	16
Disc Brake System	18
Antilock Brake System	19
Vehicle Dynamics Control Brake System	20

Table 20 Design requirement numbers of vehicle brake systems

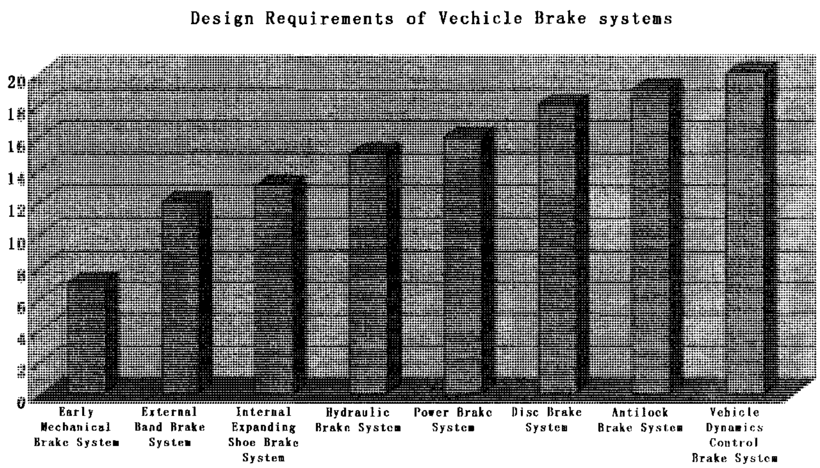


Figure 62 Design requirement numbers of vehicle brake systems 1

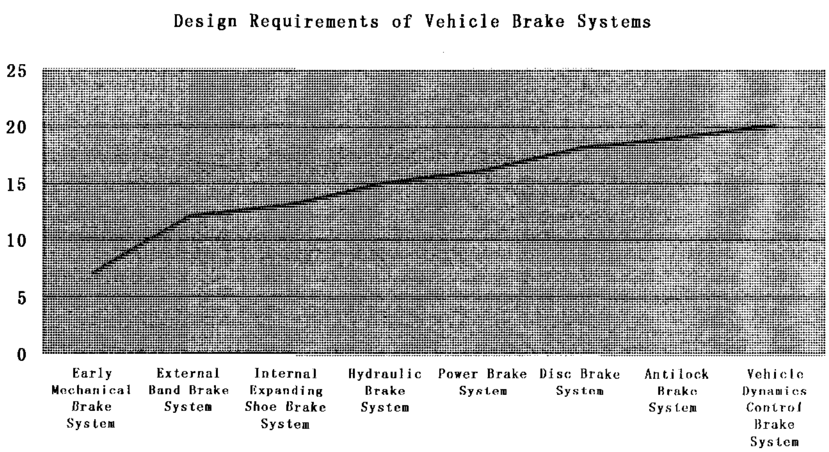


Figure 63 Design requirement numbers of vehicle brake systems 2

All these suggest that designers could make full use of product environment analysis from the beginning of the design processes, so as to predict the right design direction and increase design effectiveness and efficiency.

Chapter 7 Conclusion and Future Work

Having finished comprehensive studies, all predetermined objectives have been well achieved. Environment-based Design methodology is proven to be valid to develop industrial design process.

Design driving forces are conflicts between different environment components of the product system (Zeng, 2004b). Actually, such conflicts are contradictions between human environment components (human being) and other environment components. Specifically, they embody in the gap between increasing human needs and functions of existing product systems. Then something new (new product) must be designed to remove the conflicts and balance the system.

Design requirements directly or indirectly come from conflicts between environment components. Design requirements can be obtained by analyzing the relations between product environments. After the design requirements are analyzed and classified, some of the most important tasks are selected and considered for subsequent design work.

Environment-based Design method can provide designers with a well-organized design model, and proved to be an effective tool to formalize design process. It was comprehensively applied and verified in the simulative design of early mechanical brake system.

A design concept consists of some basic subsystems named design sub-concepts. In certain order and structure, these design sub-concepts are organized into an integral design concept. A design sub-concept should satisfy some design requirements or remove some environment conflicts. The integral design concept should integrally remove the environment conflicts (design driving forces), and satisfy design requirements. So the criterion of a qualified design is if the new design removes the conflicts and balances the product system.

Laws or trends about how a product develops were studied by analyzing the evolution of brake systems. Change of environment is the immanent cause of product evolution. Change takes place daily, and nothing remains the same. Product environments keep changing all the time. These changes sometimes can result in environment conflicts or possibility to remove existing environment conflicts.

A new product system usually evolves and improves from its predecessors. The new product system trends to involve more and more product environments. It often needs to satisfy most design requirements of all precedent product systems. Designers have to consider new environment components to search for new design requirements in the design processes. All these suggest that designers should make full use of product environment analysis in their design processes, so as to predict the right design direction and increase design effectiveness and efficiency.

Certainly, we should also acknowledge that, Environment-based Design (EBD) methodology still has much that needs improving. So some research work is necessary to make the theory more optimal and detailed. Also, practical industrial trials are expected to validate EBD further. Finally, some active popularization is in urgent need, and then people will stand a good chance of knowing, studying, and eventually accepting and applying the theory.

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