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# Brake System Design Optimization. Volume I A Survey and Assessment

A. T. Kearney, Inc., Chicago, Ill

Prepared for

Transportation Systems Center, Cambridge, Mass

Jun 78

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# BRAKE SYSTEM DESIGN OPTIMIZATION
## Volume I: A Survey and Assessment

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FINAL REPORT



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16. Abstract


Existing freight car braking systems, components, and subsystems are characterized both physically and functionally, and life-cycle costs are examined. Potential improvements to existing systems previously proposed or available are identified and described in functional and economic terms. Innovative braking systems which offer a potential benefit are identified, described, and assessed for functional and economic characteristics. Potential improvements are divided into two categories: those which could be implemented in the short term (10 years) and those which could be implemented in the long term (20 years). Areas which need additional study are identified.


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## PREFACE

The work described in this report was carried out under the direction of the Transportation Systems Center of the U. S. Department of Transportation in the context of an overall project of the Federal Railroad Administration (FRA) to provide a technical basis for the improvement of rail transportation service, efficiency, productivity and safety. The work was sponsored by the FRA Office of Research and Development, Office of Freight Systems.

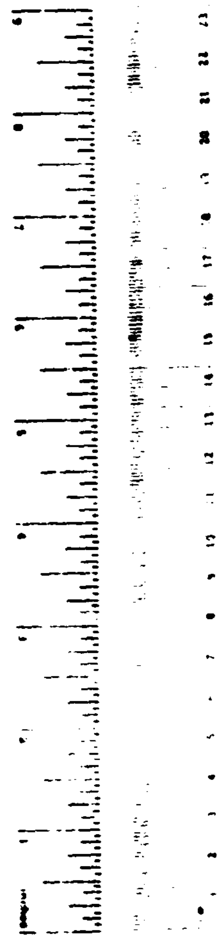
This final report is organized into two volumes. Volume I describes the work performed and presents the results of the study and is a complete report. Volume II contains supporting materials developed in the course of the study which add substantially to the information base but are not essential to the object of the study.

Kearney gratefully acknowledges the cooperation of the many railroads, rapid transit companies, manufacturers, research and development organizations, AAR Brake Equipment Committee members and staff, and other interested parties who provided the information required to conduct a professional, objective study. We would also like to thank DOT personnel in the Transportation Systems Center and the Federal Railroad Administration for their cooperation and assistance throughout the course of the study.

## METRIC CONVERSION FACTORS

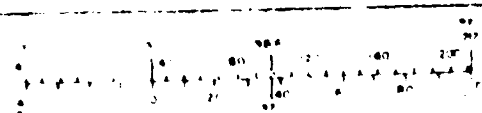
### Approximate Conversions to Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |



### Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



## EXECUTIVE SUMMARY

This report is a survey and assessment of freight train braking technology. The historical events that occurred in the development of freight train air brake systems are discussed first, followed by a detailed description of the life cycle cost and functional performance characteristics of air brake systems and components, including estimates of the population of the components presently in service. The report then presents an assessment of the overall brake system performance characteristics as they affect train handling, stop distance, and grade balancing power. Results of implementing innovative variations of the key train braking performance characteristics were investigated using the computerized Train Operations Simulator (TOS) developed by the Association of American Railroads. Finally, conclusions and recommendations were developed that delineate the steps that should be taken to achieve improved freight train braking safety and performance over both the short and long terms.

Volume I of this report was structured to contain the degree of detail adequate to support the findings and conclusions, without obscuring the pattern in which each section was developed. Volume II contains substantially more technical detail than Volume I, and as such represents an information and data base that supports Volume I.

The present freight train air brake system represents the culmination of years of improvement made to the basic brake system adopted in 1933 when the "AB Valve" was approved for general use by the Master Car Builders. This braking system consists of a single pneumatic train line that is manually connected between cars, and a pneumatic control valve on each car. The single pneumatic train line performs two basic functions: (1) it provides the brake energizing energy for each car in the form of compressed air which is stored in a reservoir on each car, and (2) it communicates control signals in the form of pressure changes which are interpreted by the control valve on each car, which in turn causes the car brakes to be applied and released.

Although the basic system initially provided adequate braking performance and safety margins and exhibited favorable cost characteristics, the demands placed upon it over the years have been severe. Freight train tonnages, lengths, and speeds have increased several fold since the turn of the century. To meet these demands, many improvements have been necessary. These include the development of more sophisticated and faster reacting control valves, the introduction of composition brake shoes, the use of welded brake pipe fittings to reduce leakage, improved freight car wheel metallurgy that can withstand increased thermal loads, and many others.

However, these improvements in technology were not totally adequate in preventing a deterioration in freight train braking performance. To prevent this detoriation the industry also resorted to two supplementary methods of increasing braking levels to meet these increasing demands. These methods included a general increase in brake system air pressures and increased use of locomotive dynamic brakes.

The increases in brake system demands are still occurring, primarily because of the continuing influx of high gross-to-tare ratio freight cars into the North American Fleet. Unfortunately, it does not appear that the solutions used in the past will solve the problem in the future. The brake control valve designers are now faced with the fundamental physical limitations concerning the sensitivity that can be incorporated into the valve when the valve must depend upon the single pneumatic train line for its control inputs.

Because the brake system on a freight car is single capacity, that is, it does not self-adjust for empty and loaded car conditions, any further increase in brake pipe air pressures would cause severe wheel sliding problems in a train consisting of both loaded and empty cars. The ability to increase braking levels is constrained by the wheel and brake shoe thermal capacity limitations now encountered with severe braking. The increased use of locomotive dynamic brakes is not advisable because of train dynamics and reliability considerations.

While many of the braking demands could be relaxed by the operation of shorter freight trains, it is the consensus of the project team that this is not likely to occur. The overall conclusion, therefore, is that unless several innovative steps are taken immediately, braking performance will deteriorate. The net effect of this deterioration would be that freight trains would have to be operated at lower speeds downgrade, and at lower speeds elsewhere unless signal spacings are increased. This in turn would cause a decrease in rail freight hauling capacity by the entire railroad industry.

This report includes the methods by which freight train braking performance could be improved within the short term (10 years) and long term (20 years). While substantial amounts of technical and economic research will be required in support of these methods, the methods were structured so that major problems associated with equipment compatibility and initial cost have been taken into consideration by utilizing the experience of the project team.

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## LIST OF ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| AAR | Association of American Railroads |
| ARA | American Railway Association |
| ARCI | American Railway Car Institute |
| ASME | American Society Of Mechanical Engineers |
| BCP | Brake Cylinder Pressure |
| BHP | Brake Horsepower |
| CFM | Cubic Feet Per Minute |
| COT&S | Clean, Oil, Test & Stencil |
| C&NW | Chicago & North Western |
| E-P | Electro-Pneumatic |
| GRL | Gross Rail Load |
| HP | Horsepower |
| ICC | Interstate Commerce Commission |
| IDT&S | In Date Test & Stencil |
| kips | Thousand Pounds |
| L/V | Lateral/Vertical |
| MCB | Master Car Builders |
| mph | Miles Per Hour |
| NBR | Net Braking Ratio |
| NTIS | National Technical Information Service |
| PRR | Pennsylvania Railroad |
| PSI | Pounds per Square Inch |
| T/OB | Tons per Operative Brake |
| TOS | Train Operations Simulator |

# 1. INTRODUCTION AND BACKGROUND

## 1.1 OBJECTIVES

The objectives of the research documented in this report were the following:

1. to develop a physical characterization of existing freight car braking system components and subsystems;

2. to provide a functional characterization of braking systems performance and response in terms of individual freight cars and for entire trains;

3. to provide an assessment of the life-cycle costs of existing freight car braking systems (specifically excluded from these costs were costs related to safety, derailments and injuries and costs related to train delays by air brake malfunctions);

4. to identify, describe, and assess potential improvements that might be made to existing freight car braking systems concepts;

5. to provide an assessment of innovative braking systems identified in the study, based upon their respective impact upon functional and cost characteristics;

6. to identify areas which appear to warrant additional research.

## 1.2 SCOPE

The scope of the study included freight train braking systems relevant to railroad operations in North America. Specifically excluded from the study were passenger train systems, and freight and passenger locomotive braking systems. No original research concerning advanced braking system concepts was intended, nor did the study include the design or invention of advanced systems.

## 1.3 APPROACH

The approach used to perform the study was one of collecting and assembling relevant existing information and data to provide a comprehensive assessment of existing freight train brake systems, potential improvements, and possible innovations.

The means used to obtain the required data and information varied depending upon the particular objectives and types of information and data required. The general techniques employed included (1) performing literature searches, (2) interviewing rail freight car brake system component suppliers, (3) interviewing railroad research organizations, (4) soliciting information from rail system and private car owners, (5) utilizing data and information bases provided by rail associations and governmental bodies, and (6) utilizing the collective experience and data bases compiled by the members of the consulting team. In addition, several advanced braking concepts were evaluated using the TOS computer model developed by the Association of American Railroads.

## 1.4 ORGANIZATION OF THE DOCUMENT

This document comprises five sections followed by three appendices. The content of each of the sections which follow are:

Section 2 - Historical Perspective on Railroad Freight Car Braking Technology. This section traces the evolution and development of present freight train air brake technology beginning in the middle 1800's. The separation of passenger train and freight train braking techniques is discussed, and the evaluation of freight train braking regulations from both the industry and the government is presented.

Section 3 - Characterization of Existing Railroad Freight Car Braking Technology. This section presents a brief description of the principles of operation of freight train brake systems, estimates of the number of brake system components presently in service, and estimates of the life cycle costs associated with existing freight train braking technology.

Section 4 - Opportunities for Innovation in Railroad Freight Car Braking Systems. This section presents and discusses the past trends in freight train brake system performance demands, discusses the implications of the methods used by the suppliers and the railroads to meet these demands, and presents alternative improvements and innovations for freight train braking. It also includes preliminary analyses of the potential performance of several innovative concepts that appeared to have merit.

Section 5 - Conclusions. This section presents a brief summary of brake system performance and trends, and suggests possible remedial actions for short term (10 years) and long term (20 years) time frames.

Three appendices are also included:

Appendix A - Glossary of Terms. This appendix presents and defines the terminology typically used by the air brake and railroad industry.

Appendix B - References and Bibliography. This appendix presents a documentation of the materials used in the study.

Appendix C - Report of Inventions.

# 2. HISTORICAL PERSPECTIVE ON RAILROAD FREIGHT CAR BRAKING TECHNOLOGY

## 2.1 INTRODUCTION

The purpose of this section is to provide a historical perspective of the evolution of freight car systems of today. This section is not intended to be a detailed history on the development of braking systems or braking technology, but rather is a summary of the salient events, conditions, and decisions that affected the development of freight train braking technology. The sources used in compiling this section were:

1. interviews with professionals in the air brake industry,

2. interviews with personnel active in the railroad industry,

3. literature reviews.*

The topics discussed in this section are orgainzed as follows:

a. Evolution of equipment,

b. Evolution of freight train braking regulations,

c. Summary.

## 2.2 EVOLUTION OF EQUIPMENT

Beginning about 100 years ago, two parallel evolutionary patterns in the development of rail freight equipment can be identified. These patterns are the Evolution of Freight Cars and the Evolution of Brake Development.

### 2.2.1 Evolution of Freight Cars

Freight car design has undergone many substantial transitions within the past 100 years. Many of these transitions have

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* For a thorough review of the history of air brake development, see three articles authored by D. G. Blaine, published in Trains Magazine. (1975a, 1975b, 1976).

had an effect upon braking requirements, including changes in freight car capacity, type, length, and gross-to-tare ratio.

2.2.1.1 Freight Car Capacity - During the late 1800's, freight car capacities of 20 to 30 net tons were typical. Today, however, the standard freight car capacity ranges between 70 to 100 net tons, with 125-ton capacity not uncommon.

The increase in freight car capacity occurred over a substantial number of years. In the late 1800's, when steel was introduced in freight car construction, cars of 40-ton capacity began to appear in number, and in the early years of the twentieth century, 50-ton capacity cars were introduced.

Between 1900 and the beginning of World War II, the 40- and 50-ton cars had become the standard, while the 30-ton capacity cars had virtually disappeared. Also, during this period, cars of 70-ton capacity were introduced.

The 50-ton capacity freight car remained as the standard car for several years following World War II. By 1960, however, the 70-ton cars were becoming the standard, and the 90-ton capacity cars were first introduced.

During the 1960's, the 100-ton capacity car was introduced. This portion of the car fleet is growing rapidly at this time, and the 100-ton car can be considered as the standard capacity car of the 1970's. Also during this period, without increasing the number of wheels, cars of 125-ton capacity were introduced.

In summation, the capacity of freight cars has increased by a factor of five times in approximately 100 years. This rapid increase in freight car capacity produced severe demands upon freight train braking technology.

2.2.1.2 Function of Freight Cars - Between the 1800's and today, there has also been a dramatic change in the function of freight cars. This has created a proliferation of many types and sizes of specialized freight cars which have been introduced to capture particular sectors of the freight transportation market.

In the late 1800's, most rail freight tonnage was transported in three or four basic car types: the box car, the flat car, the stock car, and the hopper car. Today, however, there are many kinds of freight cars ranging from the short, high-capacity ore cars, to the 89-foot long "Hi-Cube" and flat cars that carry finished automobiles, automobile parts, highway truck trailers, and containers. Furthermore, because of the the many variations in coupler draft gear characteristics installed on these long cars, the typical freight train has become difficult to operate from the standpoint of braking and controlling slack action within the train.

2.2.1.3 Freight Car Length - Freight cars of the late 1800's carried brake pipes of 25 to 35 feet in length. In contrast, today's long cars have brake pipes over 100 feet in length. Because of the physical limitation on the sensitivity of the brake control inputs this increase in car length, combined with a substantial increase in number of cars in a typical train, has created large demands on the pneumatically operated air brake systems developed during the period.

2.2.1.4 Gross-to-Tare Ratio - The increases in freight car capacity, the increases of car and train length, and the proliferation of the many car types have each created substantial demands on freight train braking technology. Also affected by these and other changes have been one of the most important brake design parameters - the gross-to-tare ratio.

The gross-to-tare ratio is defined as the loaded gross rail weight of the car divided by the tare (also called the empty or light) weight of the car. With the 20- to 30-ton cars of the 1800's constructed of wood, the gross-to-tare ratio was on the order of 2:1. Today, however, the 100-ton capacity hopper cars constructed of light weight steel (or aluminum) have gross-to-tare ratios on the order of 4:1. Unless the air brake system on an individual car can produce different braking levels depending upon whether the car is loaded or empty, the design braking level of the car must be compromised. This compromised level of braking must be restricted to a maximum level such that when a train brake application is made, the wheels of the empty cars in the train do not slide. The resulting variations in car deceleration rates among empty and loaded cars within a train create large in train slack action forces. This and related air brake system characteristics are discussed in greater detail in Section 3.

### 2.2.2 Evolution of Brake Development

In the middle 1800's the subject of railway safety was a very significant public issue; thus, much effort was directed toward developing reliable braking systems. The major developments are discussed below.

2.2.2.1 Steam Brake - One of the first major freight car brake inventions was a steam brake that was used on steam locomotive drivers. The steam brake was introduced in Scotland in 1833 and in America in the 1850's.

The steam brake was demonstrated to be unsuccessful in North America because of the extreme cold winter weather which caused the water vapor in the brake to freeze and render the brake useless.

2.2.2.2 Vacuum Brake - In 1860 a second major type of brake system was introduced - the vacuum brake. Modifications of this brake are still in use on a few railway systems throughout the world.

The vacuum brake did not prove to be the most advantageous braking system for use in North America because of its fundamental operating limitations. The primary limitation of the vacuum brake is that its effectiveness is a function of the atmospheric pressure at the location in which the brake is being used. This is especially significant because in many instances the most serious braking demands are those encountered in mountain operations.

2.2.2.3 Compressed Air Brake - In 1867, George Westinghouse conceived and patented the basic air brake concept of using compressed air to operate train brakes.

The Westinghouse air brake system was first demonstrated in a passenger train in Pittsburgh, Pennsylvania in 1869. This brake, which did not work on the same principle as today's automatic air brake, applied air pressure from an air compressor on the locomotive directly to the brakes on the cars of the train. This system, known as the straight air brake is shown schematically in Figure 2-1.

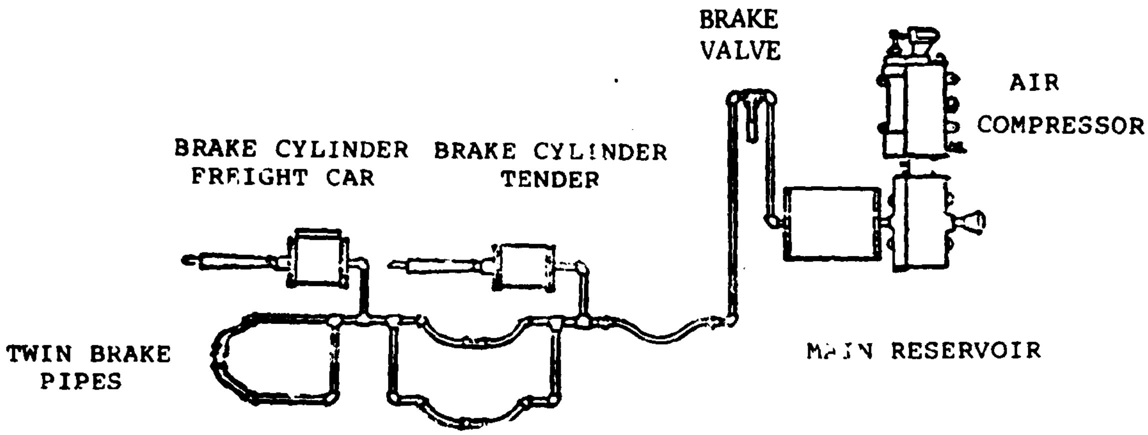



FIGURE 2-1

WESTINGHOUSE STRAIGHT AIR BRAKE

The straight air brake was far superior to the vacuum brake, since it would produce the same brake force at any altitude and had higher effective pressures permitting the use of smaller brake cylinders. However, in the event that a train pulled apart or uncoupled while in motion, there would be no source of braking energy to stop the portion of the train separated from the locomotive. This lack of a "fail-safe" feature was recognized by George Westinghouse as a serious deficiency.

In 1872, Westinghouse introduced the first "automatic" air brake. A schematic of this brake is shown in Figure 2-2.

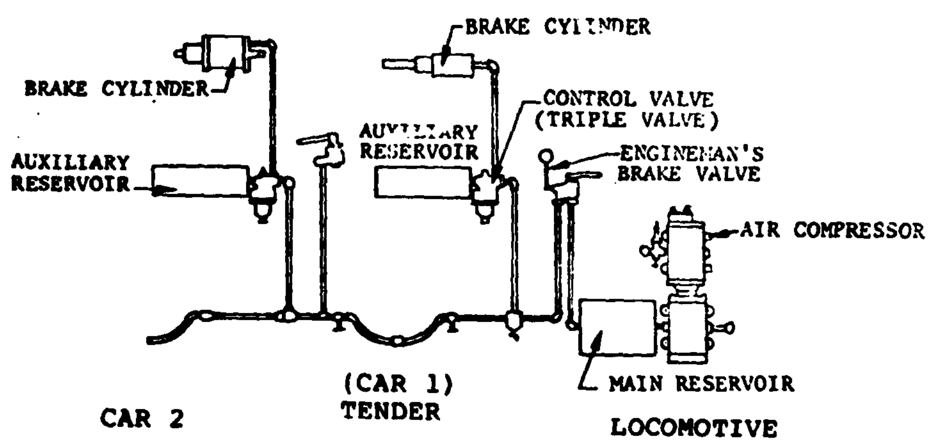



FIGURE 2-2

**WESTINGHOUSE "PLAIN" AUTOMATIC AIR BRAKE**

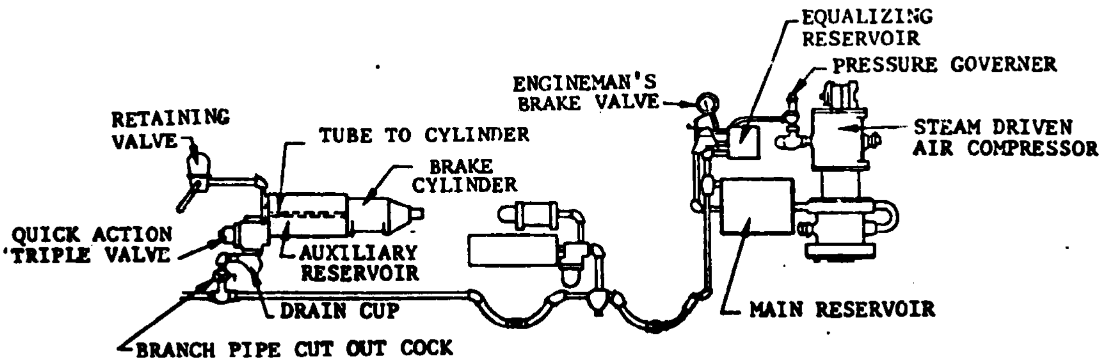
The automatic air brake, which was automatic in the sense that it was fail-safe in the event of a train separation, incorporated an air reservoir on each car which stored compressed air that could be used to apply the car brakes through a series of brake control valves, brake cylinders, and rigging.

2.2.2.4 More Advanced Air Brake Designs - During the 1870's there existed substantial competition between the various brake design concepts, which included mechanical, vacuum, and compressed air types of brakes. Consequently major tests were conducted in 1886 and 1887 at Burlington, Iowa, under the auspices of the Master Car Builders Association. The purpose of these tests was to measure and compare various brake systems under similar operating conditions with 50-car trains. The results of these tests clearly demonstrated that the compressed air brake concept was the preferred design. However, the results were not entirely satisfactory in that even with the Westinghouse automatic air brake, severe in-train forces resulted when the brakes were applied. The in-train forces resulted from the brake application speed being slower than the natural run of slack and the relatively large amounts of free slack existing in the coupler system.

To speed up the brake application signal throughout the train, Westinghouse introduced an electronic signal wire for use in conjunction with the air brake system. This was the first use of the so-called electropneumatic brake system on rail freight cars. Because this system was very successful, the Master Car Builders (MCB) recommended the electropneumatic system as the desired standard in 1887. However, this decision was quickly reversed by the railroad industry members who were unenthusiastic about dealing with a new brake system on their cars, especially if it incorporated the relatively crude electrical components of the 1880's.

Westinghouse again attempted to improve the response time of the automatic air brake without the use of the electric wire signal. This led to the development of the so called "quick action" triple valve which was more sensitive in sensing service and emergency rate of brake pipe reductions and consequently closely matched the performance of the electropneumatic system. This improvement prompted the MCB to adopt the new valve as the standard for new car construction in 1889. This valve was the forerunner of the braking systems utilized in the North American rail freight industry today.

A schematic of the Westinghouse "quick action" automatic brake is shown in Figure 2-3.




CAR 2 (CAR 1) TENDER LOCOMOTIVE

FIGURE 2-3

SCHEMATIC OF THE WESTINGHOUSE
"QUICK ACTION" AUTOMATIC AIR BRAKE

In summation, the major developments in braking technology between 1833 and 1900 are listed below:

1833 - Steam Brake for Locomotive Drivers Introduced in England.

1850's - Steam Brake Unsuccessfully Tested in North America. The results were not acceptable.

1860 - Vacuum Brake Introduced.

1867 - Air Brake Conceived and Patent Filed by George Westinghouse.

1869 - Air Brakes First Demonstrated on a PRR Train.

1870 - Tests on the C&NW Led to Rapid Acceptance of the Westinghouse System.

1872 - First "Automatic" Air Brake Introduced.

1879 - Freight Car Air Brakes Were Introduced with Combined Reservoir, Cylinder, and Control Valve.

1883 - Pressure Retainer Valve Introduced, Single Brake Pipe System Practical for Grade Operations.

1886 - Comparison Testing of Air, Vacuum and Mechanical Brakes Held at Burlington, Iowa.

1887 - Electrically Operated Brake Valve Introduced, Second Year of Burlington Trails.

1888 - "Quick-Action" Triple Valve Introduced.

1889 - "Quick-Action" Automatic Air Brake Adopted as Standard for Interchange Trains by MCB.

1894 - High Speed Passenger Car Brake Introduced.

As shown in this list, there were a number of developments in air braking technology during the period between 1883-1894. For the most part, however, many of the inventions were never adopted as standard features. In particular, the electropneumatic brake system was first introduced to the rail freight industry in 1887, was accepted and recommended by Master Car Builders but was rejected by the railroads. Had the electropneumatic brake been accepted in 1887 and refined for the past 90 years, as have the present air brake systems, the overall impact on the rail freight industry might have been substantial.

2.2.2.5 Post-1900 Developments - In the period of time since 1900, the emphasis has been placed upon improving and refining the operation of the basic Westinghouse "quick action" automatic air brake system. This has included improvements in brake valve design, increases in brake rigging efficiency, new brake shoe materials, and the introduction of specialized brake control devices.

At the turn of the century the emphasis in braking was placed on improving passenger train braking performance. Passenger train speeds of over 50 mph were common. The use of high (110 PSI) brake pipe pressures in conjunction with cast iron brake shoes (which characteristically increase friction as speed decreases) caused a problem when trains were decelerated to a stop from high speeds. While the high speed deceleration rates produced were proper, the stopping characteristics were too severe, causing abrupt stops and passenger discomfort. "

To reduce the level of braking in the low speed range, a "high speed reducing valve" was used to "blow down" brake cylinder pressure when the lower speed ranges were entered. This valve, which did not sense speed, performed the brake cylinder blow down in about a one-minute time period. Consequently it only worked properly for the correct combination of train speed, train length, and grade.

In 1904, Westinghouse introduced a "graduated release" feature to provide better control of train deceleration rates. By increasing brake pipe pressure in 2-to-3 PSI increments after an application had been made, a proportional reduction in brake cylinder pressure could be produced, thereby reducing the decelaration rate as zero speed was approached. This feature was first applied in large numbers on the Interboro Rapid Transit equipment in New York City.

In 1906, the "L" triple valve was introduced for main line passenger service. The "L" triple valve incorporated the graduated release feature as an integral part of the control valve. It was at this point in history that the development of passenger and freight train braking systems continued in separate directions.

In the period of 1910-1915, larger capacity (50- and 70-ton) coal and ore cars were introduced in significant numbers into freight operations. These cars, which had significantly higher gross-to-tare ratios than the cars in existence at the time, posed a great challenge to the air brake designer. This brought about the "empty-load" brake device, which provided two different levels of braking on a car, depending upon whether the car was empty or loaded. Although early versions of empty-load equipment had to be set manually in the "empty" or "loaded" position, later versions were designed to determine automatically whether a freight car was empty or loaded. Even with this improvement, there are presently very few freight cars equipped with empty-load devices today.

Immediately before World War I, a brake valve designated as the "K" valve had become the MCB standard for freight trains. It was also during this period that train lengths and tonnage increased dramatically. Consequently, reports of train slack action became frequent enough to attract the attention of investors who wanted to propose a new type of brake valve. One feature of the proposed brake valve was the provision of a "graduated release" feature for freight service.

In 1924, the Interstate Commerce Commission (ICC) held hearings for the purposes of developing specifications for the features which were to be incorporated in the freight braking system. The American Railway Association (ARA) was given the responsibility for testing the individual concepts and finding a practical combination of improved features that could be incorporated in a new brake system. The results of the testing of the graduated release feature were summarized as follows:

> The graduated release function failed dismally on trains of any significant length. It was impossible to obtain satisfactory and safe speed control down grades with 65 to 70 cars that had only 3,500 feet of brake pipe. During graduated release operation, much dead time was spent "bleeding off," or manually releasing the rear third of the train. Slack control was poor, and shocks and pull-aparts were common. (Blaine, 1975b, p. 53).

The ARA tests did, however, produce a replacement brake valve for the "K" brake valve. The replacement valve, known as the "AB" valve, was developed in the late 1920's and became the standard valve for new car construction in 1933.

The "AB" valve was considered a very significant advancement in freight car braking technology, primarily because on 150-car trains having 7,500 feet of brake pipe it provided a much faster brake application response time than the "K". In addition, the "AB" valve had a controlled buildup rate of brake cylinder pressure in emergency; this produced a slower, more gentle brake application, which tended to minimize slack action forces.

The "AB" brake valve remained the standard freight train brake valve until quite recently, and still represents the dominant type of brake control valve in service today (see Section 3).

In summation, the major steps in braking technology between 1900 and 1945 were:

1900 - Compatibility of Westinghouse and New York Air Brake Assured by Sang Hallow Tests on PRR.

1902 - Magnetic Brake Introduced for Electric Street Railway Cars.

1904 - Graduated Release Feature Used on Subway Equipment.

1906 - "L" Triple Valve for Passenger Service Introduced with Graduated Release.

1908 - Electro-Pneumatic Brake Introduced for Subway Systems.

1929 - "AB" Freight Car Control Valve Demonstrated.

1933 - "AB Valve Adopted as Standard for All New Freight Cars.

2.2.2.6 Post-1945 Developments - A number of new freight train brake developments have been introduced within the past 30 years. Probably one of the most significant of these developments has been the introduction of the "ABD" brake valve in the early 1960's. The "ABD" valve, which was introduced in 1962 and became the standard for all new cars in 1974, incorporated an accelerated service release feature. In addition, the "ABD" valve has offered reduced maintenance requirements, which not only reduce costs but also tend to improve reliability.

Within the past two years other advanced brake valves have been introduced. One of these valves, known as the "ABDW" valve, has undergone tests and was recently accepted by the AAR as standard. The "ABDW" valve has been designed to provide a faster and more uniform braking response throughout a train.

Although this section has dealt primarily with advancements in brake valve design, there have also been developments in other brake components.

In 1958 a direct-acting truck-mounted type of brake rigging was introduced to rail freight operations. Known by the trade names of Wabcopac and Nycopac, the direct-acting brake rigging differs significantly from the conventional types of rigging. In the conventional systems a brake cylinder is located on the car body and transfers the brake application forces to the brake shoes through a series of rods and levers mounted to the car. In the direct-acting system the brake cylinders are located on the trucks of the car and the application forces are transferred directly to the brake beams supporting the shoes. The direct-acting system offers more efficient and uniform braking force application to the wheels of the car. Both of these types of rigging are discussed further in Section 3.

A second major development in freight train braking technology since 1945 has been the high-friction "composition" brake shoe. The composition brake shoe is composed of synthetic materials as compared to the standard cast iron brake shoe. In addition to permitting lower brake shoe forces to obtain equivalent braking levels, the composition brake shoe produces more favorable thermal loadings and better wheel wear characteristics (see Section 3).

Other developments since 1945 include the introduction of welded brake pipe fittings on cars to reduce air leakage, a pressure-maintaining feature as an integral part of the "26-L" locomotive brake valve and an improved, high phosphorus content metal brake shoe. These and other developments are summarized below:

- 1958 - Direct Acting (truck-mounted) Brake Introduced.
- 1960 - Composition Brake Shoes Introduced.
- 1961 - Pressure-Maintaining "26-L" Locomotive Brake Valve Introduced.
- 1962 - "ABD" Brake Valve Introduced.
- 1966 - "ABD" Valve Given General Approval.
- 1967 - Welded Fittings Required for All New Cars.
- 1971 - High-Phosphorous Brake Shoe Introduced.
- 1974 - "ABD" Valve Became the Standard for All New Cars.
- 1974 - "ABDW" Brake Valve Accepted.

## 2.3 EVOLUTION OF FREIGHT TRAIN BRAKING REGULATIONS

The previous section summarized the development of freight train braking technology in terms of equipment, namely, freight cars and air brake system components. It is the purpose of this section to summarize the evolution of freight train braking regulations during the same period.

During the past 100 years, many of the developments in air brake technology resulted from freight train braking demands that underwent almost revolutionary changes. Train tonnages increased from 2,500 tons in the last century to 25,000 tons today, a tenfold increase. Train speeds increased from 20 mph to 80 mph, a fourfold increase. These events in combination with the introduction of many types of cars with different gross-to-tare ratios and draft gear characteristics created severe demands upon braking technology.

To enable the rail freight industry to adapt coherently to these demands in braking technology, several organizations have been formed throughout the years to develop standards and regulations governing freight train braking performance, design, and operation.

### 2.3.1 Regulation Within the Railroad Industry

Before the turn of the twentieth century, the railroad industry played a predominant role in the development of brake system performance standards. This was accomplished through the Master Car Builders Association (MCB) which was founded in 1867.* During the 1870's and the 1880's the MCB conducted a number of tests of braking systems. These tests resulted in the first train brake system performance specifications in 1895.

The MCB, and its successor the Association of American Railroads (AAR), have continued to work in this area to the present time. One of the more recent landmarks of this effort was the development in 1933 of the basic AAR brake performance standards.

The primary agency within the AAR today that deals with freight train brake technology is the Brake Equipment Committee** of the Mechanical Division of the AAR. This committee is composed of representatives from rail companies and private car-lines. The Committee meets on a regular basis to handle all

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* The Master Car Builders Association formed the basis for the Mechanical Division of the Association of American Railroads (AAR).

** Formerly the Brake & Brake Equipment Committee (B&BE).

matters of business relating to braking systems. This included the approval of new components for use in the North American freight car fleet and the continued updating of "Standards and Recommended Practices" for brake systems currently in use. The role of the AAR today is:

1. Establish construction standards for new cars and new equipment,

2. Recommend standards for the functioning of brake equipment,

3. Certify new equipment as acceptable and meeting AAR standards,

4. Establish maintenance requirements and recommend maintenance procedures,

5. Maintain records and provide billing service for work done on cars in interchange.

The Brake Equipment Committee functions through the technique of deliberation and balloting, with the emphasis being on the total welfare of the rail freight industry in terms of safety and economic viability.

The primary device for compliance with the AAR's standards and practices is exercised through the AAR Interchange Rules. Under the Interchange Rules, an individual railroad may refuse to accept cars at interchange from another railroad if the cars offered in interchange do not satisfy the standards and practices set forth by the Brake Equipment Committee.

### 2.3.2 Regulation by the Federal Government

Government involvement with the standards for freight train braking technology has come about at the Federal level through various acts of Congress.

The first Congressional Act was the Federal Safety Appliance Act of 1893. This act required that all trains be composed of cars equipped with power brakes, and that a sufficient number of the cars in a train be equipped with power brakes controlled by the engineman in the locomotive.

Since 1893, the laws of Congress were changed and updated on a number of occasions. Probably the most significant changes occurred separately in 1910 and 1958. In 1910 the Congress required that a train brake test be performed to demonstrate that the brakes operate properly before the train leaves the initial terminal and that at least 85 percent of the cars have operative brakes. In 1958, the Federal Government gave the power of law to the various standards that had been developed by the AAR over many prior years through enactment of the Power Brake Law of 1958.

Today, the primary Federal agency dealing with brake standards and regulation is the Office of Railroad Safety of the Federal Railroad Administration (FRA), which functions through normal rulemaking procedures, enforcing its rules through a series of field offices and enforcement agents. This role includes:

1. Establishment of minimum requirements for brake equipment operation to permit operation of trains,

2. Establishment of standards for the functioning of equipment in train service,

3. Provision for inspection of equipment on a random basis,

4. Leveling of penalties against those that fail to comply with federal standards.

The primary emphasis of the FRA with respect to train braking technology is safety. The penalty for noncompliance with the FRA regulations is a fine.

A summary of the development of industry and government regulations is presented below:

1867 - Master Car Builders Association Formed to Establish Interchange Rules.

1870 - Standing Committees Established for Wheels, Axles, Power Brakes and Couplers.

1884 - MCB Adopts All-Metal Trussed Brake Beams for Truck Standardization.

1886 - MCB Conducts Burlington Tests.

1887 - MCB Recommends Electrically Operated Brake Valves as Standard.

1889 - Quick Action Automatic Air Brake Adopted as Standard.

1893 - "Federal Safety Appliance Act" Passed.

1895 - B&BE Committee of MCB Issues First Train Brake System Performance Specification.

1910 - Safety Appliance Act Requires 85% of Cars Equipped With Power Brakes Operable by the Engineman.

1933 - Basic AAR Standards Adopted for Power Brakes.

1958 - Federal Power Brake Law Adopted.

A comparison of the nature of air brake regulation between industry and government is summarized below:

<u>Industry</u>

Primary Agency Is AAR Brake Equipment Committee Which:

a. Operates under manual of standard practices,

b. Functions through committee research, deliberation, and balloting,

c. Emphasizes total rail industry welfare,

d. Penalizes for noncompliance by denial of interchange.

<u>Government</u>

Primary Agency Is The FRA Which:

a. Operates under federal power brake law,

b. Functions through agency rule making procedures and field offices for enforcement,

c. Emphasizes safety,

d. Penalizes for noncompliance by collecting a fine.

### 2.3.3 Train Stop Distance Requirements

The railroad operating and braking standards presently in effect in Europe have been developed on a substantially different basis than those of the United States. Compared to Europe, freight train operations in the United States typically involve larger trains that are operated over longer distances. On the other hand, European freight operations tend to include trains that operate at somewhat higher speeds, although this is not universally true.

As a result of this and other factors, the European braking standards specify a maximum train stop distance for all trains regardless of operating speed. This specification differs substantially from the standards in the United States.

In the United States, braking standards are oriented towards individual brake system component performance with allowance for variables, such as train lengths and gross-to-tare ratios. Although there is no stop distance specified for any given speed, there is a specification published in the Code of Federal Regulations, Title 49, Paragraph 236.24 which relates train stop distance to signal spacing, as follows:

Maximum Train Stop Distance Requirements Implicit in the United States Code of Federal Regulations:

> "Each roadway signal shall be located with respect to the next signal or signals in advance which govern train movements in the same direction so that the indication of a signal displaying a restrictive aspect can be complied with by means of a brake application, other than an emergency application, initiated at such signal, either by stopping at the signal where a stop is required, or by a reduction in speed to the rate prescribed by the next signal in advance where reduced speed is required."

The above regulation states that the maximum speed for any train is that which allows the speed to be reduced to conform with the indication of the next signal ahead with an application of the brakes of other than emergency.

For the case of an absolute stop signal indication, the train must be able to stop with a full service application within one signal block distance. Furthermore, this requirement implies that, for trains operating down steep descending grades with block signals, the brake application necessary to balance the grade must be no more than approximately half of a full service application. This is necessary to assure a sufficient reserve braking capacity to stop on a grade if necessary without using an emergency brake application.

### 2.3.4 North American Air Brake Design Criteria of the Past

It is difficult to speculate what the exact criteria have been which affected the decisions made in the development of braking systems in North America. It can be assumed that the vastness of North America and the diversity of rail operations played a significant role in these decisions. Other factors, which are also considered today, are the first cost of new components and the requirement that improved components must be compatible with existing systems.

Inevitably, any workable system represents a compromise. In its desire for improved reliability and lower costs, the North American rail freight industry is presently emphasizing the need for brake equipment that has a low initial cost combined with simplified maintenance requirements involving nonsophisticated techniques.

## 2.4 SUMMARY

The evolution of today's freight train air braking systems has been affected by several factors.

From the beginning of air brake system development, the emphasis has been placed on safety in the sense that sufficient braking capacity and reliability were required in order to stop a train under all conditions.

During the early period of air brake development, some rather sophisticated braking concepts were developed and tested. It is of particular significance that the electro-pneumatic brake came extremely close to becoming the standard brake system as long ago as 1887, but was not accepted by the rail freight industry because of the required retrofitting of the cars in existence at the time, and the unproven reliability of electrical devices of the period.

By rejecting the electropneumatic brake system, the rail freight industry, for all practical purposes, accepted the Westinghouse "automatic" air brake as the standard design concept in North America, a position it has maintained since 1889.

Stimulated by revolutionary increases in train tonnages, increases in train and car lengths, a proliferation of car types, and substantially increased train speeds, the development of freight train braking technology has been based upon improving the Westinghouse automatic brake by improving individual air brake system components within the overall constraint of maintaining compatability with existing systems.

In the early 1900's, the "empty-load" device was designed to cause the brakes on empty and loaded cars in a train to react differently to the same control input. This technique has often been considered for general use, particularly within recent years with the introduction of cars with gross-to-tare ratios on the order of 3:1 or greater. However, the empty-load device was never required as a standard component of freight train braking systems in North America and is used on a voluntary basis on only a small percentage of the car fleet today.

Also introduced in the early 1900's was the graduated-release feature of brake system operations. Although adopted for use in passenger service and commonly found in use on European railways, the graduated-release feature has not been used in North American rail freight operations. One reason for this is that for a graduated release feature to function properly on long trains, the system must incorporate an improved communication signal such as an electric signal similar to that incorporated in an electro-pneumatic system.

Freight train air brake regulation is presently governed by two agencies -- one private and one governmental. The emphasis of the regulations of these two agencies with respect to braking technology is to provide rail industry welfare and operating safety, respectively. Although brake system component performance specifications ultimately manifest themselves in overall braking performance, train braking performance standards such as minimum deceleration rates or maximum train stop distances are not explicitly specified in the standards developed by these agencies, although the train stop distance requirement is implicitly specified in terms of signal spacing and train operating speeds.

Although various suppliers of air brake components have demonstrated the capability of improving braking performance, the present interest of the rail freight industry is focused upon brake systems of low initial cost and simplified, less frequent maintenance requirements.

# 3. CHARACTERIZATION OF EXISTING RAILROAD FREIGHT CAR BRAKING TECHNOLOGY

## 3.1 INTRODUCTION

This section presents a characterization of existing railroad freight car braking technology in terms of operations, functional performance, population of components in service, and life cycle costs. The arrangement and content of this section is as follows:

1. Operations:

   A simplified description of the mechanics of train brake operations is presented. Following this, a description is presented of the impact of regulatory inspection requirements as they affect the handling of train brake systems in train makeup and operation.

2. Functional Performance:

   This section comprises a characterization of freight train braking performance.

3. Components in Service:

   Estimates are provided of the population of brake system components presently in service and the kinds of components presently being purchased by the railroad industry. Also included are brake system problems and recommended solutions identified by members of the railroad industry.

4. Life Cycle Costs:

   The life cycle cost estimates of the installation, inspection, and maintenance of present brake systems are presented.

5. Summary:

   A summary is provided at the end of this section which includes the salient developments of the section.

## 3.2 OPERATIONS

To form a basis for the remainder of this section and the entire report, the operations of freight train braking systems are described from the two aspects of Mechanics of Operation, and Inspection and Handling.

3.2.1 Mechanics of Operation

This section describes the mechanics of train brake operation by describing the operation in terms of typical brake system components and freight train makeup. The emphasis is placed upon describing the response of individual brake system components on a car in a train during the initial charging and during brake application and release.*

3.2.1.1 Description of Typical Freight Car Brake System - Figure 3-1 illustrates the components of a typical brake system, which mutually interact to the control input provided by the engineman.

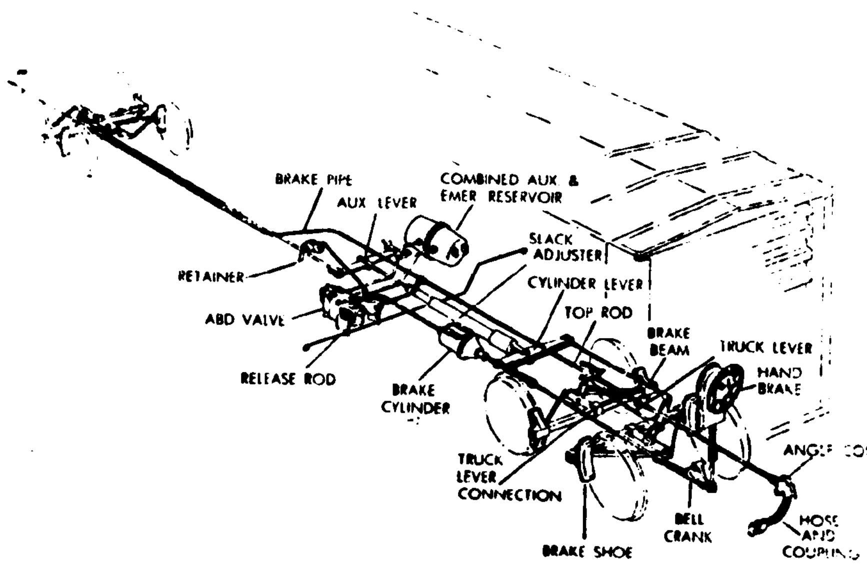


FIGURE 3-1

COMPONENTS OF A TYPICAL FREIGHT CAR BRAKE SYSTEM

**Source: Air Brake Association (1972). (Copyright - used by permission.)**

*** For a detailed description of the mechanics of train brake operation and use please refer to <u>Management of Train Operation and Train Handling</u>, The Air Brake Association, 1972.**

The brake system on a freight car consists of pneumatic and mechanical portions. The pneumatic portion of the brake system performs the two functions of (1) controlling the brake operation and (2) producing the braking force by means of permitting compressed air to enter the brake cyclinder and react against the piston inside of the cylinder.

The mechanical portion or rigging of the brake system also has two functions. The rigging (a) amplifies the braking force produced by the piston in the brake cylinder through a system of rods and levers, and (b) distributes the braking force to each of the eight brake shoes on the car.

Because the operations of the brakes on a car in a train are controlled by the pneumatic portion of the brake system of the car, the description of the operations can be assisted by referring to Figure 3-2, which shows the pneumatic portion only.

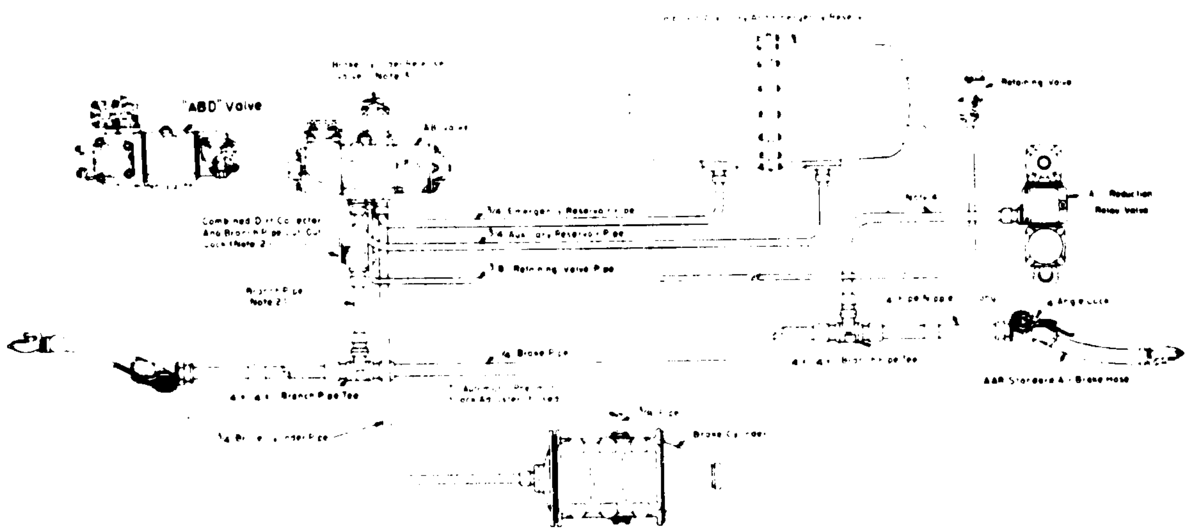


FIGURE 3-2

**TYPICAL PNEUMATIC PORTION OF THE BRAKE SYSTEM OF A FREIGHT CAR**

**Source: Air Brake Association (1972). (Copyright - used by permission.)**

The operation of the pneumatic portion is discussed next.

3.2.1.2 Initial Charging of a Train Brake System - Beginning with a train that has been "made up" at its initial terminal, the brake system on each car in the train must be supplied ("charged") with compressed air. Charging can begin only after all of the air brake hoses have been connected between cars and after all of the angle cocks have been verified to be in the "open" position. (The rear angle cock on the last car of the train, typically the caboose, must be placed in the "closed" position to restrict air from escaping.)

Train brake charging is normally performed by the air compressors on the locomotive consist. Air is pumped through the air hoses and brake pipes of the cars and enters the separate auxiliary and emergency compartments of the air reservoir. The air pressure continues to increase until it reaches the feed valve setting on the locomotive, for example, 70 PSI.

3.2.1.3 Brake Application (Service) - Brake application now could be accomplished by the engineman positioning the brake handle on the locomotive brake control stand to the "service" position. This would permit air to exhaust gradually (at a "service" rate) from the brake pipe in the train through a small orifice in the locomotive brake control stand until the brake pipe pressure reduces to a predetermined pressure; for example, from 70 PSI to 64 PSI. (This would be called a "6-pound service reduction.")

The "AB valve"* on each car would now sense that the pressure in the auxiliary reservior is greater than the brake pipe pressure (70 PSI versus 64 PSI) and would interpret this condition as a service brake application command.

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* Brake control valves exist in several versions; for example, "AB", "ABD", "ABDW", and "ZlA". While each of these valves have different performance features, their basic function is the same. In discussing brake system operations, the term "AB valve" is normally used in a generic sense to connote any basic valve, rather than specifically the AB type of basic valve.

To apply the brakes, the "AB valve" would permit compressed air stored in the auxiliary reservior on the car to enter the brake cylinder to produce the desired braking force. Air would continue to flow from the auxiliary reservoir to the brake cylinder until the air pressure in the auxiliary reservoir dropped to the current brake pipe pressure (64 PSI in this example).

An additional, larger brake application could now be made by the engineman making a further reduction in brake pipe pressure. The "AB valve" on each car would permit an additional amount of compressed air to flow from the auxiliary reservior on the car to the brake cylinder, and increase the braking force.

Because the "AB valve" on each car permits a fixed volume of stored air at a given initial pressure to flow from the auxiliary reservoir to the brake cylinder, and because brake cylinder volume increases as the piston in the brake cylinder is displaced to operate the brake rigging, the volume-pressure relationship of the auxiliary reservoir and the brake cylinder can reach a point where the pressure of the air reservoir and the brake cylinder are equal. This point, known as a "full service" application, represents the maximum braking force that can be produced at a service rate. Any additional brake pipe reductions made at a service rate would not produce an increased braking force after the full service equalization point has been established.

3.2.1.4 Brake Application (Emergency) - In the above description of a full service application, the only way additional braking force could be produced within the train would be to make use of the compressed air stored in the emergency compartment of the air reservoir on each car.

An emergency brake application is accomplished by making a rapid decrease in brake pipe pressure regardless of its current value. This is accomplished by the engineman placing the brake handle in the "emergency" position. A rapid drop in brake pipe pressure (as opposed to a gradual drop during a service application) would be sensed by the "AB valve" on each car, and would be interpreted as an emergency brake application command. The "AB valve" on each car, upon sensing the rapid drop in brake pipe pressure, would perform two functions: it would locally vent an additional amount of brake pipe air to assist in "communicating" the emergency command to the "AB valves" on the other cars in the train, and it would allow both auxiliary air (if the auxiliary pressure is greater than the current brake cylinder pressure) and emergency reservoir air on each car simultaneously to enter the brake cylinder on each car.

It should be noted that any event causing a rapid rate of brake pipe pressure reduction will cause an emergency application of all brakes in the train. For example, if a moving train pulls apart or uncouples, causing the air hoses between the two cars involved to separate, the air in the brake pipe would escape instantaneously, causing a very rapid rate of brake pipe pressure reduction. This rate would be sensed by the "AB valves" as an emergency command, and all the brakes in the train would be set in emergency. This is the "automatic" feature designed by Westinghouse described in Section 2 and has more recently been referred to as the "fail safe" feature of the present train brake system.

An "undesired emergency" brake application could also result if an air hose ruptures or separates from its mate, or if a brake valve on a car is overly sensitive. Also, if train air leakage is sufficiently great and intermittent, an emergency brake application could be produced.

3.2.1.5 Brake Release - The train brakes can be released by the engineman placing the brake handle on the locomotive brake control stand to the "release" position. This would permit air from air compressors of the locomotive consist to enter the train brake pipe.

The increasing brake pipe pressure would be sensed by the "AB valve" on each car and would be interpretted as a release command. The "AB valve" on each car would allow the air from the brake pipe to recharge both compartments of the reservoir on each car, and would permit air to exhaust from the brake cylinder through the retaining valve to the atmosphere.

### 3.2.2 Inspection and Handling Associated with Freight Train Brake Systems

Brake system inspection requirements and handling associated with freight train operations consumes a significant portion of time and resources of rail freight transportation. A description of the inspection requirements and handling processes is presented next.

3.2.2.1 Train Preparation for Departure - The air brake preparation for a train departing from an initial terminal requires a substantial amount of time and labor.

First, the air hoses between cars must be inspected for damage, and must be manually connected between cars. Angle cocks must be checked to assure that they are properly positioned (open). In addition, brake shoes must be inspected and replaced with the proper type (composition or metal) if they are worn beyond the condemning limits. (For cast iron shoes the condemning limit is 1/2 inch of remaining material; for composition shoes the limit is 3/8 inch.)

The air reservoirs and brake pipe in the train must be charged with compressed air, either from the locomotive consist, or from "plant air" facilities in the yard. The time required to charge a train depends upon the length of the train, the amount of leakage throughout the train, and the capacity of the air compressors of the locomotives or yard plant. Typical train charging times are seldom less than 5 to 10 minutes, and can approach an hour; for a given leakage rate they increase approximately linearly with train length for trains of more than 50 cars. (Leakage, which is adversely affected by cold weather, can extend these times considerably.)

After the train has been charged to within at least 15 PSI of the locomotive feed valve setting and to not less than 60 PSI as measured at the rear of the train, the brakes may be applied by making a 15 PSI service brake pipe reduction. At this point all brakes must apply, and brake pipe leakage must not exceed 5 PSI per minute. If these conditions are satisfied, a full service reduction is made and the entire train is inspected to determine that brake cylinder piston travel is within prescribed limits (between 7 and 9 inches), that all brakes are applied and the brake rigging is not binding, and that the brakes remain applied until brake pipe pressure is restored to release the brakes.

Following the inspection of the train brake aplication, a release signal may be given to the engineman. After the brakes release on the rear of the train, the train may depart. During the departure a "roll by" inspection is made to verify that all brakes in the train have released.

3.2.2.2 Over-the-Road-Operation - The inspection requirements of trains operation over-the-road are minimal. However, a number of problems that are associated with the brake system can occur.

Brakes of individual cars in the train can fail to release for various causes and lead to "dragging brakes." Dragging brakes generate wheel temperatures and sparks which can activate track wayside infrared hot journal detector alarms. This requires the train to be stopped, walked, and inspected to isolate the true cause of the alarm. If it is determined that the alarm was activated by dragging brakes, the problem is normally corrected by releasing the hand brake, or by isolating ("cutting out") the air brake system of the car involved by closing the cutout cock located between the brake pipe and the "AB valve" on the car, and "bleeding" the air from the brake system of the car. Other causes such as binding rigging, or malfunctioning slack adjusters are difficult to correct on the road.

Air hose rupture or separation can also cause problems in over-the-road operations. In addition to the disruption of service and time required to correct the problem, the resulting undesired emergency brake application could cause severe slack action forces, resulting in damaged equipment, lading, or derailment.

3.2.2.3 Intermediate Terminals - If the train or locomotive consist is changed in any way at an intermediate terminal, the train must be charged and a brake test must be performed to assure that the brakes on the rear car apply and release properly. If the train consist is changed at points other than a terminal, the train must be charged, a leakage test must be performed, and a brake test must be made to verify that the brakes apply and release on the rear car.

3.2.2.4 500-Mile Inspection - An inspection of the brake system must be made at least every 500 miles from the previous inspection point. This inspection includes the leakage test, the application and release test, and an inspection to verify that the brake rigging is properly secured and does not bind or foul.

3.2.2.5 Destination Yard - At the destination yard the air brake system of each car must be manually "bled" so that the cars roll freely during switching and classification. The bleeding process typically is performed by the car inspection teams as they inspect the mechanical condition of the cars. During this inspection process the inspection teams also check the date stenciled on the car that indicates when the most recent periodic cleaning, oiling, and testing (COT&S) of the brake system was performed. If the car is due for the COT&S, it is "bad-ordered" and sent to the nearest available car shop qualified to perform the COT&S.

3.2.2.6 Periodic Cleaning, Oiling and Testing - There are two types of periodic maintenance that are performed on freight cars to assist in the proper functioning of the air brake system: the In-Date Test and Stencil (IDT&S) and the Clean Oil Test and Stencil (CCT&S). A useful description of these tests and their effects is contained in Blaine, D.G. and Hengel, M.F., "Brake-System Operation and Testing Procedures and Their Effects Upon Train Performance," ASME Paper 71-WA/RT-9.

3.2.2.7 Summary - As described above, a significant amount of time and labor related to the present air brake system are consumed in handling a car from origin to destination and in performing periodic maintenance. Estimates of the direct costs of this handling and maintenance are provided in this section under the heading of Life Cycle Costs.

## 3.3 FUNCTIONAL PERFORMANCE

The nature of freight train braking performance specifications* is oriented towards the performance of brake system components as contrasted to overall train braking performance specifications in terms of train minimum deceleration rates or maximum stop distances. While the component performance specifications ultimately manifest themselves in actual train braking performance, large variations in train braking performance can result depending upon the mix of brake system components found in a given train.

This section discusses the impact of the present AAR brake performance specifications in detail, describes the functional performance characteristics of selected brake system components and subsystems, provides estimates of train stop distances, and delineates performance problems presently associated with present braking technology.

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* Association of American Railroads, 1975b.

### 3.3.1 Impact of Present Performance Specifications

The functional performance of freight train braking systems can be described with respect to two parameters; namely (1) brake system response and (2) braking level. Both of these parameters affect train stop distance and in-train slack action forces.

3.3.1.1 Brake System Response - Brake system response involves the time elements that occur between the instant a control command is initiated and the time when all train brakes reach their steady state braking level. For example, a brake application command made by the engineman requires a finite time to propagate through the train. An additional time is required from the instant the command is received by the brake valve on a car and full braking force is developed. This propagation time produces a serial action of brake response within the train.

3.3.1.2 Braking Level - The braking level produced on each car of a train not only depends on the nature of the command received by the brake valve on the car but also is strongly dependent upon the design and condition of the brake system of the car. Consequently, even though two cars in the same train might ultimately receive the same command, the braking levels they produce could be substantially different. Variations in braking levels within a train could result from a number of sources. Two of these include (1) improperly functioning brake system components, and (2) brake system design fundamentals accepted by the industry that do not provide adequately uniform braking levels among all cars in a train.

Improperly functioning brake system components are known to exist; however, rigorous industry inspection and testing efforts detect gross malfunctions in brake system operation. On the other hand, the design fundamentals currently used governing the design levels of freight car braking permit large variations in braking forces to be produced by different cars within a train.

3.3.1.3 Net Braking Ratio (NBR) - The key parameter used as a performance specification in the design of brake systems today is the Net Braking Ratio (NBR). The acceptance by the railroad industry of the Net Braking Ratio was a major improvement over the previously used parameter of Gross Braking Ratio. However, the required use of Net Braking Ratio in the design of freight car braking systems results in substantially different braking levels within trains consisting of loaded and empty cars.

The Net Braking Ratio is defined as the total brake shoe force developed (between the shoes and the car wheels) by a brake cylinder pressure of 50 PSI, divided by the weight of the car. For a car equipped with composition brake shoes, the design NBR must be greater than or equal to 6.5 percent when the car is loaded, and less than or equal to 30 percent when the car is empty. As shown below the use of this definition of NBR to produce the design level of braking inherently produces substantially different theoretical car deceleration rates, depending upon whether the car is being operated in loaded or empty condition in a train:

1. <u>NBR Requirements</u>

| Empty Car (30 tons) | Loaded Car (130 tons) |
|---|---|
| NBR $\leq$ 30% | NBR $\geq$ 6.5% |

2. <u>Design Calculations</u>

Assume car is designed to satify the maximum empty-car NBR (30%).

By definition,

NBR = (Total Brake Shoe Force) $\div$ (weight of car) or:

NBR = BSF $\div$ W then:

$$\begin{aligned} BSF &= NBR \times W \\ &= (0.30) \times (60{,}000 \text{ lbs.}) \\ &= 18{,}000 \text{ lbs.} \end{aligned}$$

Because the same BSF would result when the car is loaded, the loaded NBR would be:

$$NBR = \frac{BSF}{W} = \frac{18{,}000}{260{,}000} = 6.9\%$$

which satisfied the condition that loaded NBR $\geq$ 6.5%.

3. Comparison of Deceleration Rates

The Force of Retardation (F) equals the Brake Shoe Force (BSF) times the Friction Coefficient (C) of the brake shoe (for composition shoes this is approximately 33%), F = BSF x C.

| Empty Car | Loaded Car |
|---|---|
| F = BSF x C<br>= 18,000 x 0.33<br>= 5,940 lbs. | F = BSF x C<br>= 18,000 x .33<br>= 5,940 lbs. |

The deceleration rate (D) equals the Force of Retardation (F) divided by the mass of the car, D = F ÷ M, where M is the weight (W) divided by the gravitational constant (g) of 32.2 ft./sec.$^2$.

| Empty Car | Loaded Car |
|---|---|
| D = F ÷ (W/g)<br>= 5,940 ÷ (60,000/32.2)<br>= 3.19 ft./sec./sec. | D = F ÷ (W/g)<br>= 5,940 ÷ (260,000/32.2)<br>= 0.74 ft./sec./sec. |

Thus, the deceleration rate of the car when it is empty would be more than four times the deceleration rate of the same car when it is loaded. It is apparent from this theoretical example how a mixed train consisting of both loaded and empty cars could encounter slack action forces when the brakes are applied, and how unpredictable rates of deceleration could be experienced by the engineman, even though the brake system performance specifications were rigorously adhered to in the design and construction of the brake system of each car in the train.

### 3.3.2 Functional Performance of the Present Freight Train Brake System

Because of the extreme variations in brake system component performance and train operating characteristics, freight train stopping distance and deceleration rates can vary greatly. These effects are discussed next.

**3.3.2.1 Response of Braking System** - The brake pipe of a train has two functions: (1) providing braking energy by supplying the air brake reservoir on each car with compressed air from the locomotive, and (2) transmitting the pneumatic control signal in the form of a pressure wave to the brake "AB valve" on each car in the train.

The brake application or release signal begins at the source (typically the locomotive) and propagates back through the brake pipe of the train at a finite rate. Typically this rate of propagation ranges from between 400 to 600 feet per second for a normal service rate of application, and between 900 and 950 feet per second for an emergency application.* For a train consisting of 150 50-foot cars, the time required for the brake application signal to reach the last car in a train would require on the order of 16 seconds from the time the engineman makes the brake application on the locomotive.

At the instant the "AB valve" on a car senses the application signal, a small amount of air is allowed to flow from the auxiliary reservoir on the car to the brake cylinder. This small amount of air tends to "set up" the brakes in a short period of time; however, the total brake cylinder buildup rate is intentionally limited to prevent severe train slack action between cars. The 150th car in the train may require almost three minutes to reach its steady state braking level. The delay in achievement of steady state brake cylinder pressure produces two undesirable effects:

a. Since the brakes on the head end of the train apply first, the serial action causes the slack between cars to run forward at a rate which may be rapid and harsh, depending on rate of brake pipe reduction, speed of the train, train consist, and track profile.

b. The average braking force in the train develops slowly, producing long train stop distances. Furthermore, the engineman will not experience the rate of deceleration that the brakes will provide for almost three minutes. In the course of the three minutes, the train could enter substantially different grade profiles which might require more or less braking than in effect at the time.

The serial action of the brake system also occurs when the brakes are released. When the engineman places the locomotive brake valve in the release position, air is allowed to flow from the locomotive consist into the brake pipe of the train. This increased pressure wave signals the brake control valve on each

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* The emergency propagation rate is increased by the localized venting of brake pipe air by the individual AB control valve on each car.

car to release the air pressure from the brake cylinders and allow the air being supplied to the brake pipe to enter and recharge the air reservoir compartments. In practical cases, depending upon consist, type of brake valves, leakage, and initial brake application, brake release on the rear car may be delayed from several seconds to nearly a minute.

When the brake release is made, the "AB valve" on each car in the train completely releases the brakes (unless retaining valves are set). Partial (or "graduated") brake releases are not possible with the present freight brake system because of the physical limitations in the pneumatic system comprising the brake pipe. A graduated release feature would need to be sensitive to small pressure differentials in the brake pipe. However, it is physically impossible to transmit small pressure differential "signals" through long (7,500 feet) brake pipes with leakage (sometimes intermittent) with any degree of reliability.

3.3.2.2 Braking Level Produced by the Braking System - The braking level produced throughout the train by the responding brakes on each car is in part a function of the design Net Braking Ratio (NBR) of each car. The actual NBR's produced throughout the train can be affected by initial design level, number of loaded or empty cars, amount of brake pipe leakage, and the condition of the brake rigging. The actual train braking forces can further depend upon the predominant brake shoe and wheel friction characteristics as well as ambient conditions.

3.3.2.3 Braking Performance Criteria - Although the primary variables that affect train braking performance are Brake System Response and Braking Level Produced, the criteria that can be used to measure train braking performance are:

a. train stop distances (or deceleration rate),

b. train slack-action (coupler) forces generated,

c. grade balancing power.

Examination of the exact relationship between the brake system characteristics and the resulting brake system performance can provide an indication of the opportunities for innovation in freight train brake systems. A commonly used indication of braking performance of a freight train is the tons per operative air brake, T/OB. Excluding the locomotive, the T/OB is the total gross tonnage of the train being hauled, divided by the number of cars in the train.

The T/OB can be used as an indicator of train stop distance, deceleration rates, or grade balancing power (for given speeds or grade profiles). However, for the reasons previously described, there are many more variables required to accurately predict train braking performance.

3.3.2.4 Computer Simulation Results - To adequately consider the effects of the many variables that affect train braking performance, several computer simulation models have been developed. By selectively changing the values of the variables within practical ranges in the input to these models, the resulting effects on the train braking performance can be estimated. In addition, the use of computer simulation models also provides the opportunity to test the effects that advanced braking concepts might have on braking performance.

WABCO

Results of computer simulations performed by the Westinghouse Air Brake Division of WABCO were presented at the Air Brake Association Annual Meeting in 1974 (Hart, 1974).

The effects of variations in signal transmission rate, brake cylinder pressure buildup rate, car loading and Net Braking Ratio, and braking level were investigated in a series of simulations. (Maximum braking level during an emergency brake application can be affected by the design Net Braking Ratio (NBR) of the freight car, and by the level of brake pipe pressure carried in the train. If a high brake pipe pressure is carried, additional braking energy is stored in the air reservoir compartments. When this high pressure air is permitted by the control valve to enter the brake cylinder, a correspondingly high emergency braking level can be produced).

Simulation of an emergency brake application with higher levels of brake cylinder pressure were seen to cause higher buff draft gear forces throughout the train; the lowest overall buff forces are produced by reducing the signal transmission time (increasing the speed), thus holding pressure buildup constant.

These simulations also showed the expected decrease in train stop distance caused by increased brake cylinder pressures, as well as improvements in train stop distance associated with increased transmission signal speed and brake cylinder pressure buildup rate.

These results were obtained for a homogeneous train consist; the ultimate braking level produced by each car was the same. In actual operations, however, the braking levels produced by different cars in a train can vary considerably, partly as a result of the design NBR's and condition of each car, but most directly because of the different gross rail loads of each car. These effects were also examined. It was found that a dramatic improvement in buff forces (with a slight increase in draft forces) can be made by reducing the empty car NBR from 30 percent to 18 percent, although this would increase train stop distance.

These results were produced by holding the locomotive brakes off. Because locomotive braking ratios are typically approximately 28 percent, the draft gear forces produced by the locomotive consist are significant. The effects of various locomotive braking ratios and buildup rates were also examined. Improvements in draft gear forces were found for reduction of both the braking ratio and pressure buildup rates of brakes of the locomotives.

Train stop distance for the hypothetical 100-car train simulated was not appreciably affected by various locomotive braking ratios.

The following conclusions can be made from the computer simulation results discussed above:

1) Faster transmission signal speeds and brake cylinder pressure buildup rates produced shorter train stop distances.

2) Increasing transmission signal speed, holding brake cylinder pressure buildup rates constant, reduced slack-action forces and train stop distance.

3) Increased brake cylinder pressures (braking level) reduced train stop distance. More uniform Net Braking Ratios (NBR's) throughout the train reduced draft gear forces.

4) For the 100-car train simulated, variations of locomotive braking level did not cause appreciable changes in train stop distance, although draft gear forces were sensitive to both the magnitude and rate of buildup of locomotive braking level.

Canadian National Research Centre

Several simulations were performed by the CN Research Centre for the Association of American Railroads (Wilson et al., 1972). The computer program used for these simulations was developed by the CN Research Centre; the subroutines that calculated brake force were based on empirical models from WABCO.

The simulations were performed in two stages. The first stage involved approximately 200 simulations of inelastic models of trains to provide train stop distance and velocities during stops. The second stage involved 22 dynamic simulations to provide train slack action force data for various stopping distances.

The train consist was 3 locomotives, 96 50-foot cars of 100-ton capacity (263,000 lbs. loaded; 56,000 lbs. empty), and 1 van.

The following conclusions resulted:

1) The shortest stop distance is produced by the highest Net Braking Ratio.

2) From an initial speed of 40 mph, the full service stop distance was more than twice the emergency stop distance on a level grade.

3) For all speeds of over 48 mph, the loaded train required more than twice the stopping distance of the empty train.

4) At an initial speed of 60 mph, the full service stop distance with a mixed train required 5,100 feet, 7,000 feet, and 10,500 feet for grades of 1 percent ascending, level grade, and 1 percent descending, respectively.

5) Increased brake pipe pressure had little effect on stop distance on level grades; but, the effect was more pronounced for descending grades.

6) The exact positions of a remote locomotive unit within the train had little effect on stop distances; however, the use of a remote unit did decrease the stop distance by approximately 20 percent at a 40 mph initial speed.

In these simulations, the train was considered as inelastic -- that is, without free slack between couplers and without draft gear travel shock absorbtion characteristics. In order to investigate the dynamic effects produced by free slack and draft gear travel, the CN Research Centre produced 22 additional simulations, which illustrated the following train-dynamic effects.

a) Type of Rigging - Loaded Train: For an emergency stop with a loaded train, the truck-mounted brake rigging with composition shoes produced approximately the same level of coupler forces as the conventional brake rigging with cast iron shoes.

b) Nature of Slack Action: During stopping, trains exhibited an accordian effect, with the first slack run-in occurring at about 16 seconds being the most severe.

c) Type of Rigging - Empty Train: For an emergency stop with an empty train, the truck-mounted brakes with composition shoes produced approximately 30 percent greater buff forces than the conventional rigging with cast iron shoes. The magnitude of the buff forces was lower than the loaded train, but the magnitude of the draft forces was greater.

d) Grade Effects: The effects of ascending, level and descending grade were demonstrated with a mixed train. Coupler forces produced were high in each case; however, the forces were less severe on the descending grade and were not impulsive in nature.

e) Instananeous Transmission Signal (Emergency Application): A hypothetical instantaneous transmission propagation rate was evaluated. The peak forces were virtually the same and exceeded one million lbs. in buff, and were in excess of 500,000 lbs. in draft at car 85. There was also very little change in stop distance (about 10 percent).

f) Emergency Application; More Loaded Cars at the Rear of the Train: Placing more loads on the rear of the train increased the impulsive buff forces and extended the stop distance.

g) Loads in Front (Emergency Application): The placement of loads in the front of the train produced lower coupler forces than for the case of loads in the rear.

h) Brake Pipe Pressure: For a train with loaded cars leading, higher brake pressure (90 PSI) produced a 12 percent shorter stopping distance, but produced a draft force of slightly larger magnitude than the lower brake pipe pressure (75 PSI).

i) Instantaneous Transmission Signal with Draft Forces: The effect or providing an instantaneous transmission signal on a previously simulated condition that produced high draft gear forces produced lower impulsive forces, but towards the end of the stop the absolute draft forces were higher.

j) Full Service Application; Position of Loads and Empties: Comparison of the effects of empties in the lead versus loads in the lead during a full service application showed that the case with empties in the lead produced smoother forces, with a maximum buff force of 426,000 lbs.; with loads in the lead high draft forces were encoutered (484,000 lbs.).

k) Location of Remote Unit (Repeater Car): Placing of a remote unit two-thirds back, and at the rear of the train, respectively, showed no serious impulsive forces in either run. However, high steady draft forces were produced.

In-train dynamic forces resulting from train braking can be strongly affected by the many variables that are involved. The authors of the report summarized their work as follows (Wilson et al., 1972):

> One is forced to conclude that in-train force magnitudes during braking operations can reach dangerous levels. In order that the situation be improved, it is therefore recommended that further effort should be directed to develop "fundamental dynamic models" of the existing air brake system, so that its operation may be clearly understood. Once satisfactory dynamic models can be used in place of empirical models, it will be within the scope of researchers to develop limitations for train marshalling, train handling, and equipment selection, which will assure safety of operations under all braking conditions.

**Summary**

Component design specifications can greatly affect the overall functional performance of freight train brake systems. Computer simulations have demonstrated the complexity of quantifying the functional performance of freight trains brakes.

However, a few basic relationships can be identified as follows:

1) The distribution of loads and empties throughout the train can affect the coupler forces during brake application; however, th re does not appear to be a distribution that consistently minimizes coupler forces for different rates of brake application (service or emergency).

2) More unifrom NBR's throughout the train produce lower coupler forces. The high NBR's of locomotives increased coupler forces; the value of the NBR of the locomotive consist did not appreciably affect stop distance.

3) Faster brake system signal transmission rates can decrease coupler forces, although this was not consistently true. Faster rates of brake cylinder pressure buildup increased coupler forces. Both effects shortened the stop distance.

4) Increases in brake pipe pressure produced shorter stop distances, but caused higher coupler forces.

Table 3-1 on the following page summarizes the functional performance affects produced in train braking by various brake system characteristics.

TABLE 3-1

BRAKE SYSTEM CHARACTERISTICS AND THEIR EFFECT ON BRAKE SYSTEM PERFORMANCE

| Brake System Characteristics | Resulting Brake System Performace | | |
|---|---|---|---|
| Response | Stop Distance | Grade Balancing Power | Coupler Forces |
| Transmission Speed - High | Short | No Effect | Low |
| Transmission Speed - Low | Low | No Effect | High |
| Brake Cylinder Pressure - High | Short | No Effect | High |
| Buildup Rate - Low | Long | No Effect | Low |
| Braking Level (NBR) | | | |
| High (Uniform) | Short | Increased | Low |
| Low (Uniform) | Long | Decreased | Low |
| High (Nonuniform) | Short | Increased | High |
| Low (Nonuniform) | Long | Decreased | High |

The combination of brake system characteristics that appears to produce shorter stop distances, increased grade balancing power, and lower coupler forces is the high uniform train NBR matched with high transmission speed.

## 3.4 COMPONENTS IN SERVICE

The purpose of this section is to provide a brief description of the nature of the supply industry, and to present statistical estimates of the population of selected freight train brake system components in service today. Information is also presented concerning the types of brake system components and freight car wheels currently being purchased.

### 3.4.1 The Nature of the Supply Industry

The railway brake equipment supply industry is composed of a number of firms, most of which supply only a few components of the total brake system.

3.4.1.1 Market Entry - Probably the most complicated and sophisticated component of the brake systems in use today is the brake control valve. Currently there are two manufacturers of this valve in the United States; the Westinghouse Air Brake Division of WABCO, and the New York Air Brake Company.

The entry of other firms into this market has been uncharacteristic, probably because the brake equipment market has remained relatively stable over several years. Market stability has resulted from the railroad industry employing the practice of salvaging brake equipment from retired rolling equipment and reconditioning it in their own shops. Within recent months however, the entry of firms outside of the United States has become a possibility. One of these firms, Westcode, Inc.,* is presently in the process of testing its "Z1A" brake control valve for certification by the Association of American Railroads. If the Z1A valve is granted certification, the resulting competitive market forces could have an impact on the structure of the supply industry and the nature of products offered.

3.4.1.2 Certification of Equipment - New equipment and devices introduced to the freight train braking industry must first undergo a rigorous procedure of approval under the auspices of the Association of American Railroads (AAR). First the equipment must be submitted to the AAR for testing. In this submittal, the valve is analyzed to estimate its expected life when exposed to the severe operating environment to which it would be exposed in freight train operations throughout North America. If the equipment is deemed conditionally acceptable by the AAR, limited approval is granted for application of the equipment or device for installation on a specified small number of cars within the fleet. If the equipment performs satisfactorily within the limited approval conditions, it is granted general approval at the end of the trial period.

Upon receiving general AAR approval of the new equipment or device, the supplier may begin marketing the equipment to the railroad industry without limitation as to the quantity cr extent of use within the railroad industry.

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* Westinghouse Brake and Signal Company Limited, Railway Brake Division, Chippenham, Whilshire, England.

A following phase can be mandatory application of the equipment to all cars in the fleet, or to all new car construction. Although enactment of this phase has not frequently occurred in the past, it provides a method for a relatively rapid introduction of improved braking technology to the rail freight industry.

3.4.1.3 Services Provided by the Supply Industry - The railroad brake system component supply industry provides a very substantial service to the railroads.

One of the most significant services provided by the suppliers is research and the development responsibility they assume. Typically, railroads vote approval or disapproval of equipment recommendations from the suppliers, rather than having the supply industry respond to formally stated needs of the railroad industry.

A second important service provided by the supply industry is field service. Most large suppliers maintain extensive ranks of field engineers throughout North America to provide technical support for the railroads, and to provide input to research and development plans regarding problems being experienced in the field. The availability of these personnel is a significant asset to the industry; without them, the railroads might have to provide a more sophisticated level of engineering support.

A third service offered by the supply industry is the technical support to other agencies and persons interested in the subject of freight braking technology. The nature of the freight train braking industry is complex in terms of its heritage, its regulations, and its technology. The suppliers maintain a continuity of understanding of braking technology, without which the subject could not be readily understood by persons not closely associated with the industry.

### 3.4.2 Freight Car Brake System Components in Service

With the assistance and cooperation of the AAR Brake Equipment Committee, information was elicited from railroads and private car owners representing a substantial majority of total U.S. freight car fleet.

(a) Part A - General System Operating Conditions: Data relating to the steepest descending grades, the most severe curves, and train tonnages, lengths, and top speeds for various classes of service.

(b) Part B - Air Brake System Operations: Cold weather operating problems, use of retainer valves, success of brake cylinder release valves, slid-flat wheel problems and causes, and air brake system charging problems. In addition, opinions were sought concerning priorities in improvement of freight car braking systems.

(c) Part C - Standard Air Brake Equipment in Service: Air brake component population statistics for each of ten car types, including

- Number of cars
- Average car age
- Brake valves by type
- Brake shoes by type
- Brake rigging type
- Number of slack adjusters
- Fittings by type
- Number of load-proportional devices
- Number of empty/load devices.

Attention was also directed toward Equipment Being Purchased (by car type):

- Type of brake shoes
- Type of rigging
- Use of load-proportional or empty/load devices
- Type of wheels

(d) Part D - Special Brake System Equipment in Service: Information concerning the use of repeater relay systems, remotely controlled locomotives, and other special brake systems.

**3.4.2.1 General System Operating Demands** - Findings relating to the present brake system performance demands represented by train operations on several major railroads are summarized in Table 3-2.

TABLE 3-2

SUMMARY OF GENERAL SYSTEM OPERATING DEMANDS ON FREIGHT BRAKING TECHNOLOGY

| | Conditions | Range of Responses Minimum | Maximum |
|---|---|---|---|
| 1. | Steepest Descending Grade<br>- Main Line<br>- Branch Line | <br>1.44%<br>1.20% | <br>4.70%<br>5.89% |
| 2. | Most Severe Curvature<br>- Main Line<br>- Branch Line | <br>8.0'<br>5.4' | <br>17.0'<br>33.0' |
| 3. | Use of Helper Service | 9 of the 16 responding roads used helper service | |
| 4. | Heaviest Trains Operated | 8,000 tons | 28,000 tons |
| 5. | Fast Freight Train Characteristics<br>Maximum Length | 50 cars<br>4,300 ft | 175 cars<br>10,000 ft |
| | Top Speed | 50 mph | 79 mph |
| 6. | Slow Freight Train Characteristics<br>Maximum Length | 90 cars<br>6,500 ft | 175 cars<br>10,000 ft |
| | Top Speed | 35 mph | 60 mph |

It can be seen that the demands presently placed on freight train braking performance can be quite severe. Maximum train tonnages are as high as 28,000 gross tons, and train lenghts reach 10,000 feet (1.9 miles). Top speeds of fast freight trains are as high as 79 mph.

3.4.2.2 Air Brake System Operations - Solicitation of information concerning the use and problems with air brake systems in freight train operations, and identification of most needed improvements, yielded the results summarized in Table 3-3.

TABLE 3-3

AIR BRAKE SYSTEM OPERATIONS

| Operation/Problem | Summary of Explanations and Opinions | Number of Railroads Agreed | Number of Railroads Responded |
|---|---|---|---|
| 1. Train lengths reduced during cold weather | Reduction of train length necessary | 13 | 17 |
| 2. Use of retaining valves | Retaining valve used | 6 | 17 |
| 3. Benefits from brake cylinder release valves | Brake cylinder release valves have benefit | 15 | 17 |
| 4. Slid-flat wheel | Slid-flats are not a problem | 11 | 17 |
| | Slid-flats are caused by unreleased hand brakes | 8 | 12 |
| | Unreleased hand brakes involve truck-mounted brakes | - | 6 |
| 5. Most serious problems | | | |
| Terminals | Leakage and tests | 10 | 15 |
| | Adjusting piston travel | 3 | 15 |
| | Air hose rupture or separation | 2 | 15 |
| | Switch out cars for FRA servicing | 1 | 15 |
| | Mishandling of train brakes | 1 | 15 |
| | Water in system | 1 | 15 |
| Line-Haul | Air hose separating and failure | 10 | 16 |
| | Undesired emergency | 5 | 16 |
| | Sticking brakes | 4 | 16 |
| | Pipe fitting problems | 4 | 16 |
| | Cold weather leakage | 4 | 16 |
| | No significant problems | 1 | 16 |
| 6. Improvements that should be given highest priority | Air hose coupling and end of car arrangement | 12 | 17 |
| | Eliminate undesired emergency applications | 3 | 17 |
| | Improve brake system response times | 5 | 17 |
| | Make braking levels more uniform | 3 | 17 |
| | Use composition brake shoes | 2 | 17 |
| | Faster charging, coupling, and testing | 3 | 17 |
| | Revise regulations for testing and servicing | 1 | 17 |
| | Eliminate leakage | 3 | 17 |
| | More reliable slack adjustments | 1 | 17 |

Twelve of the responding roads identified the air hose connection and the angle cock location at the end of the car as the improvements that should be given highest priority; eight specified improved brake system performance, five roads requested faster brake system response, and three roads sought more uniform braking levels.

3.4.2.3 Air Brake Equipment in Service - The number of air brake system components in service is summarized by car type in Tables 3-4 and 3-5. These show both the absolute statistics and an estimation of the total component population of the North American freight car fleet.

# TABLE 3-4

## NUMBER OF BRAKE SYSTEM COMPONENTS IN SERVICE (BY CAR TYPE)

| Car Type: | Hopper | | Covered Hopper | | Gondola | | Tank | | Other | |
|---|---|---|---|---|---|---|---|---|---|---|
| Railroad Survey Sample Population: (1) | 249,954 | | 116,252 | | 112,852 | | 565 | | 29,675 | |
| Estimated Actual Population: | 361,242 | | 241,305 | | 200,019 | | 33,162 | | 271,014 | |
| Air Brake System Components | Percent of Cars Sampled Equipped | Estimated Population of Cars Equipped | Percent of Cars Sampled Equipped | Estimated Population of Cars Equipped | Percent of Cars Sampled Equipped | Estimated Population of Cars Equipped | Percent of Cars Sampled Equipped | Estimated Population of Cars Equipped | Percent of Cars Sampled Equipped | |
| 1. Air Brake Valves | | | | | | | | | | |
| A B | 36.7% | 132,576 | 28.1% | 67,807 | 52.9% | 109,210 | 88.9% | 26,828 | 69.9% | |
| A B Plus Brake Cylinder Release Valve | 38.0 | 137,272 | 18.6 | 44,883 | 18.4 | 30,275 | 10.1 | 6,002 | 19.9 | |
| A B D | 25.3 | 91,394 | 53.3 | 128,615 | 29.1 | 60,534 | 1.0 | 332 | 10.2 | |
| Subtotals | 100.0% | 361,242 | 100.0% | 241,305 | 100.0% | 200,019 | 100.0% | 33,162 | 100.0% | |
| 2. Brake Shoes | | | | | | | | | | |
| Metal | 65.6% | 236,975 | 33.2% | 80,113 | 62.9% | 130,044 | 91.0% | 30,177 | 49.7% | |
| Hi-Phos | 1.0 | 3,612 | 12.9 | 31,120 | 5.5 | 11,441 | 0.0 | 0 | 38.0 | |
| Composition | 33.4 | 120,655 | 53.9 | 130,072 | 31.6 | 65,734 | 9.0 | 2,985 | 12.3 | |
| Subtotals | 100.0% | 361,242 | 100.0% | 241,305 | 100.0% | 200,019 | 100.0% | 33,162 | 100.0% | |
| 3. Type of Piping | | | | | | | | | | |
| Indirect Acting (Conventional, Body Mounted) | 99.2% | 358,352 | 82.8% | 199,801 | 97.2% | 194,194 | 91.2% | 30,244 | 99.9% | |
| Slack Adjusters(2) | (52.5) | (189,652) | (55.0) | (134,640) | (40.7) | (101,305) | (10.6) | (3,515) | (20.0) | |
| Direct Acting (Truck Mounted) | 0.8 | 2,890 | 17.2 | 41,504 | 2.8 | 5,825 | 8.8 | 2,918 | 0.1 | |
| Subtotals | 100.0% | 361,242 | 100.0% | 241,305 | 100.0% | 200,019 | 100.0% | 33,162 | 100.0% | |
| 4. Type of Fittings | | | | | | | | | | |
| Welded | 25.6% | 92,478 | 48.4% | 116,793 | 40.6% | 84,456 | 3.4% | 1,128 | 14.8% | |
| Other | 74.4 | 268,764 | 51.6 | 124,512 | 59.4 | 115,563 | 96.6 | 32,034 | 85.2 | 230,904 |
| Subtotals | 100.0% | 361,242 | 100.0% | 241,305 | 100.0% | 200,019 | 100.0% | 33,162 | 100.0% | 271,014 |
| 5. Special Equipment | | | | | | | | | | |
| Load Proportional Devices (2) | None | 0 | None | 0 | None | 0 | None | 0 | None | 0 |
| Empty/Load Devices (2) | 1.8% | 6,502 | 2.0% | 4,826 | 1.7% | 3,536 | None | 0 | 2.3% | 6,233 |

Notes: (1) CARDATA records of the equipment register extracted by computer.

(2) Components not presently included in all brake system installations.

# TABLE 3-4

## NUMBER OF BRAKE SYSTEM COMPONENTS IN SERVICE (BY CAR TYPE) (CONTINUED)

| Car Type: | Box | | Hi-[illegible] Box | | Refrigerator | | Flat (TOFC/COFC) | | Flat (Non-TOFC/COFC) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Railroad Survey Sample Population: (1) | 297,869 | | 7,346 | | 72,743 | | [illegible] | | [illegible] | |
| Estimated Actual Population: | 591,928 | | 9,950 | | 102,529 | | 54,965 | | [illegible] | |
| **Air Brake System Components** | Percent of Cars Sampled Equipped | Estimated Population of Cars Equipped | Percent of Cars Sampled Equipped | Estimated Population of Cars Equipped | Percent of Cars Sampled Equipped | Estimated Population of Cars Equipped | Percent of Cars Sampled Equipped | Estimated Population of Cars Equipped | Percent of Cars Sampled Equipped | Estimated Population of Cars Equipped |
| 1. Air Brake Valves | | | | | | | | | | |
| A B | 50.9% | 301,291 | 0.5% | 50 | 34.0% | 34,860 | 12.3% | 6,760 | 49.6% | 58,472 |
| A B Plus Brake Cylinder Release Valve | 23.1 | 136,735 | 4.1 | 408 | 27.0 | 27,683 | 49.3 | 27,098 | 27.4 | 32,301 |
| A B D | 26.0 | 153,902 | 95.4 | 9,492 | 39.0 | 39,986 | 38.4 | 21,107 | 23.0 | 27,114 |
| Subtotals | 100.0% | 591,928 | 100.0% | 9,950 | 100.0% | 102,529 | 100.0% | 54,965 | 100.0% | 117,887 |
| 2. Brake Shoes | | | | | | | | | | |
| Metal | 54.6% | 323,193 | 3.4% | 338 | 27.8% | 28,503 | 93.2% | 51,227 | 48.4% | 57,097 |
| Hi-Phos | 12.5 | 73,991 | 0.0 | 0 | 39.0 | 40,007 | 0 | 0 | 22.4 | 26,407 |
| Composition | 32.9 | 194,744 | 96.6 | 9,612 | 32.4 | 33,219 | 6.8 | 3,738 | 29.2 | 34,423 |
| Subtotals | 100.0% | 591,928 | 100.0% | 9,950 | 100.0% | 102,529 | 100.0% | 54,965 | 100.0% | 117,887 |
| 3. Type of Rigging | | | | | | | | | | |
| Indirect Acting (Conventional, Body Mounted) | 96.2% | 569,435 | 21.0% | 2,089 | 92.0% | 94,327 | 84.9% | 46,665 | 93.7% | 110,460 |
| Slack Adjusters (2) | (49.3) | (291,821) | (23.7) | (2,358) | (71.6) | (73,411) | (84.9) | (46,665) | (97.2) | (87,431) |
| Direct Acting (Truck Mounted) | 3.8 | 22,493 | 79.0 | 7,861 | 8.0 | 8,202 | 15.1 | 8,300 | 6.3 | 7,427 |
| Subtotals | 100.0% | 591,928 | 100.0% | 9,950 | 100.0% | 102,529 | 100.0% | 54,965 | 100.0% | 117,887 |
| 4. Type of Fittings | | | | | | | | | | |
| Welded | 37.1% | 219,605 | 60.1% | 3,970 | 50.8% | 52,085 | [illegible] | 12,[illegible]42 | 29.4% | 34,659 |
| Other | 62.9 | 372,323 | 39.9 | 5,980 | 49.2 | 50,444 | [illegible] | 42,323 | 70.6 | 83,228 |
| Subtotals | 100.0% | 591,928 | 100.0% | 9,950 | 100.0% | 102,529 | 100.0% | 54,965 | 100.0% | 117,887 |
| 5. Special Equipment | | | | | | | | | | |
| Load Proportional Devices (2) | None | 0 | None | 0 | None | 0 | None | 0 | None | 0 |
| Empty/Load Devices (2) | None | 0 | None | 0 | None | 0 | None | 0 | None | 0 |

Notes: (1) CARDATA record of equipment register extracted by computer.

(2) Components not presently included in all brake system installations.

TABLE 3-5

ESTIMATED TOTAL NUMBER OF AIR BRAKE SYSTEM COMPONENTS IN SERVICE

| Air Brake Component | Estimated Population of Cars Equipped | Percent of North American Freight Car Fleet |
|---|---|---|
| 1. Brake Control Valve | | |
| AB | 926,209 | 46.5% |
| AB Plus | 504,589 | 25.3 |
| ABD | 561,203 | 28.2 |
| 2. Brake Shoes (Equipped Cars) | | |
| Cast Iron | 1,072,037 | 53.8 |
| Hi-Phos | 287,119 | 14.4 |
| Composition | 632,845 | 31.8 |
| 3. Brake Rigging | | |
| Body Mounted | 1,884,310 | 94.6 |
| Slack Adjusters | 965,009 | 48.4 |
| Truck Mounted | 107,691 | 5.4 |
| 4. Fittings | | |
| Welded | 659,925 | 33.0 |
| Other | 1,334,076 | 67.0 |
| 5. Load-Sensitive Devices | | |
| Load Proportional | 0 | 0 |
| Empty-Load | 21,097 | 1.1 |

3.4.2.4 Brake System Components Being Purchased - It was determined that the majority of U.S. railroads are currently purchasing the following brake equipment for replacement and new cars:

1. Composition brake shoes,
2. Conventional brake rigging,
3. About a 60/40 split in one-wear and two-wear wheels. (No load proportional devices are being purchased, and only a small number of empty-load devices.)

3.4.2.5 Special Brake System Equipment in Service - Estimates of the number of specialized brake system units in service on 16 railroads (repeater units, remotely controlled locomotives, and special types of freight car brake systems) are as follows:

| Brake System | Number in Service |
|---|---|
| Repeater Relay | 9 |
| Remote Locomotives (master and remote) | 271 |
| Special Brake System | Hydraulic-pneumatic on one car (Chessie System's articulated hopper car) |

## 3.5 LIFE CYCLE COSTS

Life cycle cost estimates associated with present freight train brake system technology are presented in this section. The elements of the total life cycle costs are arranged as follows:

1. Costs of Initial Installation of Brake System,
2. Costs of Periodic Testing and Inspection,
3. Costs of Performing Inspection and Handling Freight Cars Brake Systems in Rail Freight Operations,
4. Costs of Maintenance Associated with Wear and Damage,
5. Other Costs,
6. Estimated Total Life Cycle Costs.

Several methods exist with which to express the life cycle costs of the present air brake system. These include annual costs to the industry, the annual cost per car, and the cost per mile for different car types and utilization rates. The selection of the preferred method of expressing costs depends upon the intended use of the cost information, and the form in which the cost data is available.

The evaluation of alternate innovations in freight train braking can be performed expediently by considering the cost per car associated with the innovative device or system. This is especially meaningful since several types of innovative design might be installed on only a selective portion of the car fleet.

Expressing the life cycle costs in terms of the cost per car mile for different types of cars and utilization rates would also be desirable. Unfortunately, the cost data were not available in this form for general service freight cars, although they were available for the major car types leased by the private car owners (non-railroad owned). For this reason, the life cycle costs of the general fleet are expressed in terms of the annual costs per car; sufficient data were not available that related costs to mileage.

### 3.5.1 Costs of Initial Installation of Brake Systems

Interviews with car builders and key railroad members have confirmed that the costs associated with the initial installation of the brake system on a freight car vary substantially depending upon the type of car being equipped and the type of brake rigging selected.

Several methods were used to acquire meaningful initial installation cost data. The use of a literature search and interviews with nonrailroad freight car builders failed to produce reliable freight car brake system installation cost information. However, cost information was obtained from individuals of several railroads, and from air brake component manufacturers.

Table 3-6 presents a summary of this information from these latter two sources.

TABLE 3-6

SUMMARY OF AIR BRAKE SYSTEM INITIAL INSTALLATION COSTS
(In 1975 Dollars)

| I. Material<br>Brake System Component | Average of Estimated Installation Costs | |
|---|---|---|
| | Conventional Rigging | Truck-Mounted Rigging |
| 1. "ABD" Brake Valve, Reservoir, Brake Cylinder, and Fittings | $ 856.00 | $ 856.00 |
| 2. Hand Brake Assembly | 164.00 | 164.00 |
| 3. Slack Adjuster | 126.00 | -- |
| 4. Rigging (Conventional includes rods, bell cranks, levers, pins, etc.) | 110.00 | 110.00 |
| 5. Brake Beams | 260.00 | -- |
| 6. Brake Shoes and Keys | 50.00 | 50.00 |
| 7. Rods and Levers on Trucks | 200.00 | -- |
| | $1,766.00 | $1,180.00 |
| II. Labor | | |
| Average Estimate of 78% of Material Costs | $1,377.00 | (No estimates available for labor) |
| TOTAL | $3,143.00 | |

As shown in Table 3-6, the installation of the brake system on a typical car with conventional rigging costs approximately $3,150 per car. This amounts to about 12.5 percent of the total new car purchase price of a $25,000 freight car. Distributed over a 20-year life, the brake system installation cost would amount to approximately $160 per car per year.

### 3.5.2 Costs of Periodic Testing and Inspection

The costs of periodic inspection and testing are defined in the AAR's Office Manual of the Interchange Rules, and include the Clean, Oil, Test, and Stencil (COT&S), and the In-Date Test and Stencil (IDT&S).

According to the Interchange Rules, a COT&S must be performed on cars equipped with AB or ABD brake control valves every four years or ten years, respectively. The IDT&S must be performed if a car is shopped for any reason and 90 days have elapsed since the previous IDT&S was performed. In addition, an IDT&S is typically performed if the brake system of the car malfunctioned in over-the-road operations.

3.5.2.1 COT&S Costs - The costs associated with the COT&S vary depending upon the type of brake rigging on the car. Because the standard truck-mounted brake rigging includes four brake cylinders, COT&S maintenance costs are higher for cars equipped with truck-mounted rigging than for cars equipped with conventional rigging.

The costs shown in Table 3-7 will vary depending upon type of brake system on the car. As an example: A car equipped with one brake cylinder, (convention rigging), the established charges are less than a direct acting brake (truck mounted cylinders) that requires four brake cylinders to be cleaned. Cars equipped with additional devices or cylinders considered other than standard brake arrangement require additional time and material, thus escalating the costs for COT&S.

TABLE 3-7

COT&S COSTS AS A FUNCTION OF TYPE OF BRAKE CONTROL VALVE AND BRAKE RIGGING

| Item | Cost(1) | Cost Per Car Per Year(2) |
|---|---|---|
| ABD Brake, Truck-Mounted Four Cylinders (AAR Job Code 1060) | $297.99 | $29.80 |
| AB Brake, Truck-Mounted Four Cylinders (AAR Job Code 1004) | 237.76 | 59.44 |
| ABD Brake, Conventional Rigging Including Slack Adjuster (AAR Job Codes 1048 and 1572) | 195.58 | 19.56 |
| AB Brake, Conventional Rigging Including Slack Adjuster (AAR Job Codes 1000 and 1572) | 135.32 | 33.83 |

NOTES: (1) Source: Office Manual of the Interchange Rules, Change No. 3, October 1, 1975, AAR.

(2) Based upon a four-year period for AB valves, and a ten-year period for ABD valves.

The costs of performing the COT&S range between $19.56 and $59.44 per car per year, depending upon the type of brake control valve and the type of rigging on the car. Using this information in conjunction with the brake system component population statistics the COT&S costs were estimated as shown in Table 3-8.

TABLE 3-8

COT&S COSTS PER CAR PER YEAR

| Type of Brake System | Car Fleet Population | Cost Per Car Per Year |
|---|---|---|
| ABD, Truck-Mounted | 86,153 | $29.80 |
| AB, Truck-Mounted | 21,538 | 59.44 |
| ABD, Conventional | 531,375 | 19.56 |
| AB, Conventional | 1,352,935 | 33.83 |
| Weighted Average Annual Cost Per Car: | | $30.13 |

3.5.2.2 IDT&S Costs - The costs of performing the IDT&S are published in the Office Manual of Interchange Rules, Job Codes 1140 and 1144 (one set and two sets respectively). Because virtually all freight cars have one set of brakes, the cost of the IDT&S can be assumed to average that of Job Code 1140: $14.93

Various methods can be used to estimate the frequency of performing the IDT&S on a typical car. Statistical analysis of a large volume (over 35,000) of AAR car repair billing records indicated that the COT&S and the IDT&S consumed 3.9 percent and 4.3 percent of the total AAR billed maintenance costs, respectively. This indicates that the IDT&S costs per car per year roughly approximate the COT&S costs per car per year, namely, $27.00. At a unit cost of $14.93, this would imply that the average car received and IDT&S every 203 days.

### 3.5.3 Costs of Routine Inspection and Handling

The costs of performing routine inspection and handling of freight cars can be estimated by analyzing yard crew work element time distributions and the number of inspections received by a typical car in its load-load cycle.

The inbound inspection crews walk the train on each side and examine the brakes on each car while they are fully applied. This is done along with their normal mechanical inspection. Following the inspection, air is vented (bled) from reservoirs to permit cars to be switched without the use of air brakes. The outbound inspection crews typically connect air hoses between cars as they perform the outbound inspection. The outbound inspection crews (or "airmen") also monitor the train air brake system tests performed at the initial terminal. In addition, both types of crews replace worn brake shoes or damaged air hoses.

Figure 3-3 illustrates the percentage of inbound and outbound inspection crew time involved with different work elements.

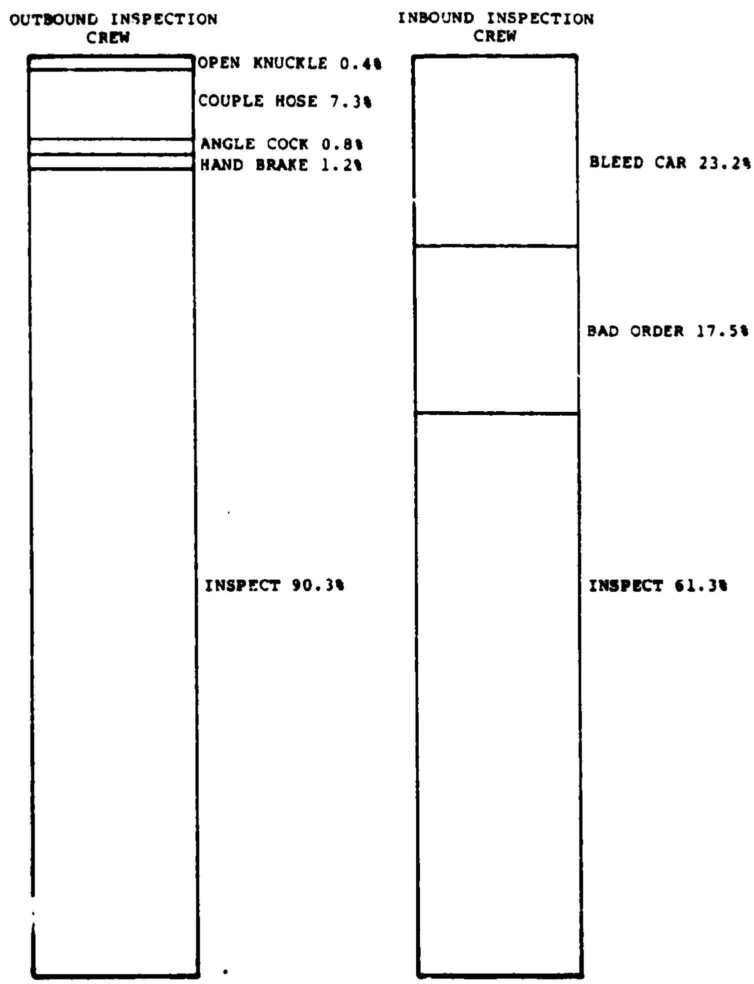


FIGURE 3-3

**INBOUND AND OUTBOUND INSPECTION CREW WORK ELEMENT TIME DISTRIBUTIONS**

**Source: A. T. Kearney time study results.**

The actual air hose coupling time requires approximately 7 percent of the outbound inspection crew time; the air brake bleeding time requires on the order of 28 percent of the inbound inspection crew time. The costs associated with air brakes can be estimated as shown in Table 3-9.

TABLE 3-9

ESTIMATED COSTS OF INSPECTING AND HANDLING AIR BRAKE SYSTEMS

| | Item | Cost (1975 Dollars) |
|---|---|---|
| 1. | Total Car Men | 40,289(1) |
| 2. | Total Annual Compensation | $509,051,500 |
| 3. | Percentage of Time Inspecting | 18% (2) |
| 4. | Annual Cost of Handling Air Brakes | $ 91,629,000 |
| 5. | Cost Per Car Per Year (2 million cars) | $ 45.81 |

NOTES: (1) "Statistics of Railroads of Class I in the United States." Association of American Railroads, August, 1974, p. 4.

(2) Figure 3-3.

As shown in Table 3-9, the estimate cost of inspecting and handling the air brake system is approximately $45.00 per car per year.

### 3.5.4 Costs of Air Brake System Maintenance Associated With Normal Damage and Wear

Data concerning the maintenance costs per car per year were obtained from a number of sources. Each of these sources are discussed separately below.

3.5.4.1 Distribution of Railroad Car Repair Expense - A large volume of car repair data (over 35,000 records) was analyzed by computer to determine the distribution of total car repair costs in terms of individual AAR Job Codes, wheels accounted for 30.4 percent; no other specific code contributed over 8 percent. The results of the analysis are presented in Table 3-10.

TABLE 3-10

DISTRIBUTION OF FREIGHT CAR REPAIR COSTS
BY AAR JOB CODE RANGE

| AAR Job Code(s) | Description | Percent of Total Cost |
|---|---|---|
| 1. 1000-1120 | COT&S | 3.9% |
| 2. 1140-1144 | IDT&S | 4.3 |
| 3. 1160-1612 | Air Brakes and Parts | 2.1 |
| 4. 1628 | Air Brake Hose | 0.5 |
| 5. 1640-1812 | Brake Rigging | 1.5 |
| 6. 1828-1852 | Brake Shoe and Keys | 4.0 |
| 7. 1856-1980 | Hand Brakes | 0.7 |
| 8. 2000-2276 | Couplers | 7.7 |
| 9. 2350-2358 | Yokes | 1.1 |
| 10. 2400-2464 | Draft Gear | 3.7 |
| 11. 2500-2570 | Lubrication | 3.4 |
| 12. 2600-2794 | Journals | 4.8 |
| 13. 2800-2882 | Roller Bearings | 7.1 |
| 14. 3000-3180 | Wheels | 30.4 |
| 15. 3200-3279 | Axles | 7.2 |
| 16. 3500-3968 | Trucks | 6.7 |
| 17. 4000-4824 | Other | 10.9 |
| | TOTAL | 100.0% |

The wheel costs associated with air brake systems were further analyzed by considering the AAR "Why Made" Codes. The distribution of wheel replacement costs by Why Made Code is shown in Table 3-11.

TABLE 3-11

DISTRIBUTION OF WHEEL MAINTENANCE COSTS BY "WHY MADE" CODE

| AAR Why Made Code | Description | Percent of Total Wheel Costs |
|---|---|---|
| 01 | Worn out | 0.8% |
| 02 | Broken | -- |
| 04 | Defective | 0.8 |
| 07 | Obsolete Material | 0.1 |
| 09 | Account Repairs | 51.7 |
| 11 | Removed in good condition account repairs | 8.6 |
| 20 | Shifted (Load or Tank) | -- |
| 25 | Owner's Request | -- |
| 33 | Derailment damage per rule 95 | 3.5 |
| 46 | Journal rusted or pitted | 0.3 |
| 49 | Journal Overheated | 0.3 |
| 60 | Flange Thin | 16.6 |
| 61 | Flange Thin - Remount | -- |
| 64 | Flange High | 9.0 |
| 68 | Rim Cracked or Broken | -- |
| 73 | Rim Thin | 0.9 |
| 74 | Thermal Cracks | 0.2 |
| 75 | Tread Shelled | 0.5 |
| 76 | Tread Built-Up | 1.4 |
| 77 | Tread Grooved | 3.9 |
| 78 | Tread Slid Flat | 0.9 |
| 79 | Tread Slid Flat with Flange Wear | 0.5 |
| 83 | Wheel with Cracked or Broken Plate | -- |
| | TOTAL | 100.0% |

The wheel maintenance costs that can be attributed to air brake system problems are as follows:

| Cause of Wheel Replacement | Percentage of Wheel Costs |
|---|---|
| Tread Slid Flat with Flange Wear | 0.5% |
| Tread Slid Flat | 0.9 |
| Tread Grooved | 3.9 |
| Tread Built-Up | 1.4 |
| Thermal Cracks | 0.2 |
| TOTAL | 6.9% |

It should be noted that interviews with professionals in the rail freight industry indicated that additional wheel wear costs can be attributed to the air brake system. However, it was difficult to quantify these additional costs.

Combining the brake released costs with the applicable portion of the wheel replacement costs results in the distribution of air brake system freight car maintenance costs shown in Table 3-12.

TABLE 3-12

AIR BRAKE RELATED FREIGHT CAR MAINTENANCE COSTS (EXPRESSED AS A PERCENTAGE OF TOTAL MAINTENANCE COSTS)

| Air Brake Related Costs | Percent of Total Car Repair Costs |
|---|---|
| COT&S | 3.9% |
| IDT&S | 4.3 |
| Air Brakes and Parts | 2.1 |
| Air Brake Hose | 0.5 |
| Brake Rigging | 1.5 |
| Brake Shoes and Keys | 4.0 |
| Hand Brakes | 0.7 |
| Wheels (6.9% of Total Wheel Percentage) | 2.1 |
| TOTAL | 19.1% |

The car repair maintenance costs associated with the air brake system can be expressed in terms of the annual cost per car by applying the percentage distribution of total repairs the national total freight car repair costs published by the ICC. Using ICC Account 314(*), Using ICC Account 314, and subtracting the car inspection costs, ($254 per car per year), results in an actual average car repair cost of $182 per car per year. The resulting estimated air brake related freight car repair costs are shown in Table 3-13.

TABLE 3-13

ESTIMATED AIR BRAKE RELATED MAINTENANCE COSTS

| Item | Estimated Cost Per Car Per Year (1975 Dollars) |
|---|---|
| COT&S | $ 7 |
| IDT&S | 8 |
| Air Brakes and Parts | 4 |
| Air Brake Hoses | 1 |
| Brake Rigging | 3 |
| Brake Shoes and Keys | 7 |
| Hand Brakes | 1 |
| Wheels | 4 |
| TOTAL | $35 |

(*) ICC Account 314 includes repairs made to freight cars. The items that were included in Account 314 by the participating railroads were identified.

### 3.5.5 Summary

The total estimated air brake system related costs are tabulated in Table 3-14.

TABLE 3-14

TOTAL ESTIMATED AIR BRAKE RELATED MAINTENANCE COSTS

| | Cost Area | Estimated Cost Per Car, Per Year (1975 Dollars) |
|---|---|---|
| 1. | Initial Installation | $160 |
| 2. | Periodic Inspection and Handling | 60 |
| 3. | Routine Inspection and Handling | 45 |
| 4. | Maintenance | 35 |
| | TOTAL | $300 |

# 4. OPPORTUNITIES FOR INNOVATIONS IN RAILROAD FREIGHT CAR BRAKING SYSTEMS

## 4.1 INTRODUCTION

In the previous section a characterization was presented of the existing state of the art in freight train braking systems. This section presents a summary of the trends within the industry that are presently affecting the demands upon freight train braking systems and their performance, and discusses possible alternative forms in which innovations might be introduced. The section is organized under the following headings:

1. Past and Present Trends: This topic describes past and present trends in traffic volume, operations, car design and brake equipment, and discusses the implications of these trends in terms of braking performance.

2. Possible Alternatives: This topic presents possible alternative brake system innovations, including improved use of present hardware, broader use of existing specialized devices, use of existing "on-the-shelf" advanced technology, and alternative patterns of train operations.

3. Summary: A summary is provided to assess collectively the topics discussed with respect to freight train braking system innovations.

## 4.2 PAST AND PRESENT TRENDS

As discussed in Section 2, the demands placed on freight train braking technology have increased by a large amount over the past 100 years. Since 1920, train speeds between terminals in some cases have increased by factors of 2 or 3, average car capacity has increased by a factor of 10. The ability of braking technology to accept these and future demands has been analyzed by several professionals in the industry. In particular, WABCO has compiled excellent statistical summaries of the trends that have affected train brake system performance. The following material represents a collective assessment of these trends and presents judgments concerning the impact these trends will have on freight train braking.

One of the primary indicators of the ability of freight train braking systems to meet the performance demands of train stop distance and grade balancing power is the effective Net Braking

Ratio (NBR) of the aggregate North American freight car fleet. The mix and size of the car fleet has changed significantly between the years of 1910 and 1973. In 1910 the freight car fleet totaled approximately 2.5 million cars; the average design Net Braking Ratio (NBR)* of the fleet was 8.3 percent. By 1973, the fleet was reduced to approximately 1.7 million cars; the average design NBR decreased to 6.6 percent. Thus, between 1910 and 1973 the number of cars in the fleet decreased by 34 percent, while an increase in average car size raised the the capacity of the fleet by 22 percent. In addition, train speeds and train lengths increased substantially.

To interpret the net effect of design NBR on the stopping distance and grade balancing power of a typical freight train, the composition of the typical train in terms of empty and loaded cars must be known. These statistics, which were complied by WABCO, are shown in Figure 4-1.

In Figure 4-1 it can be seen that the empty car NBR has begun to increase since 1960 and is projected to continue to increase as more new and rebuilt cars are added to the fleet with the empty NBR's in the vicinity of 30 percent. On the other hand, the partially loaded trains (which are more typical) show a steady deterioration in design NBR; furthermore, this deterioration is predicted to continue as additional 100-ton capacity cars with minimum loaded design NBR's enter the fleet.

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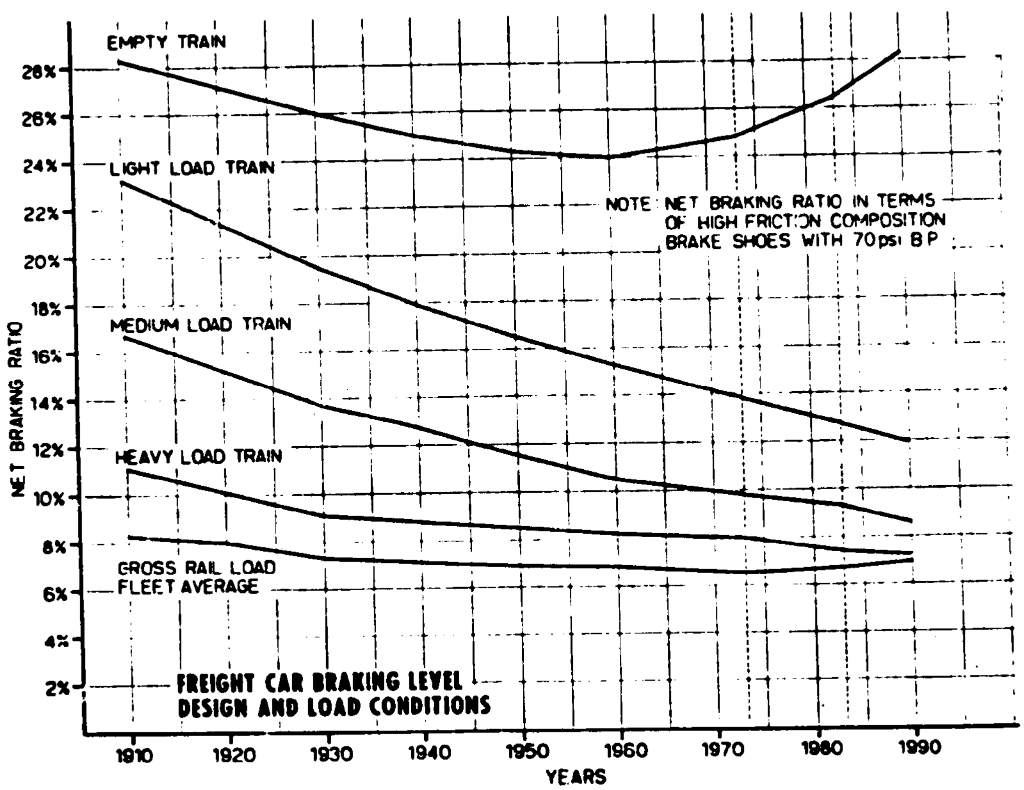
* For convenience the Net Braking Ratio is expressed in terms of high friction composition brake shoes with 50 psi brake cylinder pressure and a loaded car.




Source: WABCO, 1973, Chart 5.

FIGURE 4-1

PAST AND FUTURE TRENDS IN FREIGHT TRAIN NBR's

The above figure illustrates the effects of the design value of NBR's of cars entering the fleet since 1910. If these levels of NBR had manifested themselves as the only source of train braking during this period, train stopping distances would have increased substantially and grade holding power would have decreased. However, two forms of "supplemental" braking were introduced beginning in 1940: (1) increased brake pipe pressure, and (2) diesel-electric locomotive dynamic brakes which develop a force of retardation by using the traction motors to generate a current which is converted to heat in banks of resistor grids.

### 4.2.1 Increased Brake Pipe Pressure

The design specifications for NBR are expressed in terms of a 50 PSI brake cylinder pressure at a full service brake application. (A full service brake cylinder pressure of 50 PSI corresponds to an initial brake pipe pressure of 70 PSI.)

To obtain a higher brake cylinder pressure at full service, and therefore a higher effective NBR, the brake pipe pressure feed valve setting on the locomotive can be adjusted upward. For example, a brake pipe pressure of 90 PSI would produce a full service brake cylinder pressure of 64 PSI; a brake pipe pressure of 110 PSI would produce a full service brake cylinder pressure of 78 PSI. The increased brake cylinder pressure would produce increased braking levels, since NBR is proportional to brake cylinder pressure.

### 4.2.2 Dynamic Brake

A higher effective train NBR can also be produced by utilizing the dynamic brakes on the locomotive consist. With extended range dynamic brakes, a six-axle, 3,000-hp freight locomotive can produce a retarding force of over 50,000 lbs. Large locomotive consists can produce up to half of the braking effort required by the train.

The effects of increased brake pipe pressure and the introduction of dynamic braking on the NBR of a medium-load train were estimated by the professionals at WABCO.

The introduction of dynamic brake and increased brake pipe pressure was found to have halted the deterioration of the NBR of the typical train at the 13 percent level.

The effects of decreasing design NBR and augmented braking on train stop distance for a medium-load train were also calculated by WABCO by taking into account the primary variables affecting train braking performance. These results are tabulated in Table 4-1. Large locomotive consists can produce up to half of the braking effort required by the train.

The average train stop distance has increased and is projected to continue to increase when all variables are included in the calculations.

Since NBR also affects grade holding power, it can be assumed that the grade holding power is also decreasing for the medium-load train.

## 4.3 POSSIBLE ALTERNATIVES

As discussed above, the stop distance of freight trains has been increasing and will continue to increase according to present trends; at the same time the grade holding power has been decreasing. Some possible alternatives to improve this situation are presented below. Their effects on train slack action forces, operations, and other relevant aspects are also discussed.

### 4.3.1 Past Solutions

Train stopping distances were prevented from further deterioration by the use of supplemental train braking in the form of increased brake pipe pressures and the use of dynamic brakes. The factors which limit the further increases in supplemental braking using these forms in conjunction with present equipment are discussed below.

4.3.1.1 Further Increases in Brake Pressure - There are two primary reasons why brake pipe pressures should not be increased substantially above their present values, using present single-capacity brake equipment. First, the event of a full service (or emergency) brake application, empty cars in the train would incur wheel slide due to the adhesion demands placed upon them by an increased effective NBR.

Secondly, the effects on train slack forces from increased brake pipe pressure have been demonstrated to be undesirable using computer simulations of present brake system equipment operation (see Section 3).

4.3.1.2 Increased Use of Dynamic Brake - Dynamic brakes, when used to augment train brakes on long descending grades, can greatly aid train handling when properly used, and extend wheel and brake shoe life. However, a substantial increase in the use of dynamic brakes raises distinct problems. First, the technical problem of increasing dynamic brake capacity would have to be solved. Second, simulation results have shown that the use of locomotive dynamic brakes can cause undesirable high coupler forces within a train. Third from reliability considerations it is undesirable to depend upon dynamic brakes for a large portion of braking capacity.

Table 4-1 below illustrates the effects on train stop distance produced by dynamic brake pipe pressures since 1940.

TABLE 4-1

NORMAL TRAIN STOP DISTANCE BY YEAR

| CONDITIONS | YEAR | | | | | |
|---|---|---|---|---|---|---|
| | 1940 | 1950 | 1960 | 1973 | 1983 | 1990 |
| SPEED - mph | 38 | 38 | 4[illegible] | 46 | 47 | 48.5 |
| Number of Cars | 78 | 92 | 110 | 110 | 90 | 90 |
| Brake Pipe Length - Feet | 4,200 | 5,000 | 6,000 | 6,500 | 7,000 | 7,000 |
| Tons per Operative Brake | 45 | 50 | 55 | 75 | 90 | 100 |
| Brake Pipe Pressure - psi | 70 | 70 | 75 | 82 | 82 | 82 |
| Net Braking Ratio (Medium Speed) @ 50 psi BCP | 12.7 | 11.5 | 10.5 | 9.8 | 9.8 | 8.6 |
| Net Braking Ratio (Medium Load) @ Operating BCP | 12.7 | 11.5 | 11.1 | 11.4 | 10.9 | 10.0 |
| Dynamic Brake - Nos. Units | 0 | 3 | 4 | 4 | 4 | 4 |
| - H.P Rating | | 1,500 | 1,750 | 3,000 | 3,000 | 3,000 |
| STOP DISTANCE - Feet (Full Service Application) | | | | | | |
| - Level | | | | | | |
| o with Dynamic | | 2,750 | 3,300 | 3,625 | 4,000 | 4,350 |
| o without Dynamic | 2,750 | 3,000 | 3,700 | 4,100 | 4,400 | 4,800 |
| - 1.25% Descending | | | | | | |
| o with Dynamic | | 4,400 | 5,150 | 5,600 | 6,250 | 6,800 |
| o without Dynamic | 4,150 | 4,700 | 5,675 | 6,350 | 6,950 | 7,500 |
| Source: WABCO (1973, Chart 10). | | | | | | |

### 4.3.2 Improve Brake System Response Times

Computer simulations have demonstrated that train stop distances can be reduced without accompanying undesirable coupler forces by increasing the brake application signal transmission speed while holding brake cylinder pressure buildup time constant. It should be noted, however, that a faster response would not increase the grade balancing power of brake systems.

4.3.2.1 Faster Brake Valve Response - Train stop distance could be shortened by introducing brake control valves with quick application features similar to the "ADBW" brake control valve or the B-1 Quick Service Valve. Although the "ABD" valve provides a faster brake release feature than the "AB" valve, the "ABDW" valve provides even faster brake application. The improvement in train stop distance resulting from use of the "ABDW" rather than the "ABD," can approach 20 percent. However, fundamental physical barriers might eventually be reached in more advanced brake valve technology for which the increased sensitivity of the valves could cause the valves to misinterpret brake pipe pressure perturbations caused by other-than-control inputs (such as intermittent brake pipe leakage). This could result in undesired brake applications or undesired brake releases.

4.3.2.2 Twin-Pipe Pneumatic Brake - The addition of a second brake pipe used to constantly charge the auxiliary reservoirs could improve braking response during release. With a second brake pipe it would be necessary only to refill the volume of the original brake pipe rather than both the brake pipe and the auxiliary reservoirs. This system is used in several commuter train operations in the United States.

The performance and limitations of the twin-pipe pneumatic brake were compared to the single-pipe pneumatic brake by M. Laplaiche of the SNCF. The results of tests using the two systems were described as follows (Laplaiche, 1963, p. 756):

> ...The two pipe air brake has still its limits. The train pipe, however small its capacity, only refills at a certain speed at the end of a long train, even when the air of the reservoir is already in place. The times of release are lengthened beyond those proper to the distributor (brake valve).

4.3.2.3 Other Means of Improving Response - Brake system response can be improved by decreasing the effective length of the brake pipe. This could be accomplished by using radio-controlled remote locomotives, repeater units (radio or pneumatically controlled), or brake control modules spaced throughout the train that locally achieve brake pipe reductions by radio control.

The use of remote control equipment (designated by the AAR as RCE-1) for locomotives would not only provide faster brake application by decreasing the effective brake pipe length, but would also provide brake system recharging capability during release and would greatly reduce brake pipe gradient. In addition, several aspects of train handling could be improved provided that the engineman has reliable information and control capabilities for operating the remote unit. The advantages include great reduction in charging time, easier starting of trains (due to more uniform distribution of power), and substantially better control of train dynamics.

From the standpoint of overall train handling, it has been demonstrated that the best location of the RCE-1 unit is at the two-thirds position in the train. However, the operating problems caused by routinely locating locomotives in the two-thirds position might be reduced greatly without losing the benefits of the RCE-1 unit by locating the unit at the rear of the train. From the standpoint of train brake systems, the location of the RCE-1 unit at the rear of the train rather than at the two-thirds position produces only a slight change in the braking performance.

4.3.2.4 More Uniform Train Net Braking Ratios (NBR) - Computer simulations of train braking operations have demonstrated that large coupler forces are produced at the interfaces between blocks of loaded and empty cars. These forces can be partially attributed to the substantial differences between Net Braking Ratios of the loaded and empty cars in the train. In actual train operations, where loaded and empty cars are distributed randomly throughout the train, similar coupler forces can be developed depending upon the distribution and location of the loaded and empty cars.

As discussed in Section 3, total brake system response involves two elements: signal transmission speed and brake cylinder pressure buildup rate. Train stop distance can be decreased by speeding up the transmission signal and the brake cylinder pressure buildup rates. However, it has been demonstrated that coupler forces are extremely sensitive to the rate of brake cylinder pressure buildup rates. More uniform train NBR's could permit a faster brake cylinder pressure buildup rate with an equivalent or reduced level of in-train coupler forces.

4.3.2.5 Electro-Pneumatic (E-P) Brake System - The control of the brakes on each car could be accomplished by providing an electric circuit through the train similar to that used in mass transit and passenger operations throughout the world. While the operating requirements of such a system would probably require an advanced freight car coupler system (which also may have merit), the electro-pneumatic brake circuit could also be used to provide a "graduated release" feature which is presently not feasible for long trains using the single brake pipe pneumatic system.

Although the electro-pneumatic (E-P) brake system was tested and recommended for use by the Master Car Builders Association in the late 1880's (see Section 2), the E-P brake has never been adopted as a standard freight system in the United States.

The electro-pneumatic brake system includes magnet valves to control brake cylinder pressure in conjunction with operation of the automatic air system, and multi-wire electric circuits trainlined through each car. The automatic brake valve has a built in electric switch, which when rotated energizes corresponding electric circuits. One circuit energizes the release magnet valve located at the control valve on each car to close the brake cylinder exhaust passage to the atmosphere. A second circuit energizes the service magnet valve at the control valve on each car to admit air into the brake cylinder. The third circuit energizes an emergency magnet at the control valve on each car to locally vent brake pipe air to the atmosphere. This causes all control valves to assume emergency position at virtually the same time. The advantage of this system are:

a. Rapid response of brakes to brake valve manipulation,

b. Ability to hold brakes applied while recharging the brake system and,

c. Automatic pneumatic system operation at all times in the event of electrical failure.

#### 4.3.3 Increase Train Braking Level

An increase in the train braking level can cause both a decrease in train stop distance and an increase in grade holding power. Train braking level can be increased by increasing the loaded design NBR of freight cars with high (approximately 3:1) gross-to-tare ratios. Because the empty design NBR in use presently cannot be increased because of wheel rail adhesion limitations, the increase in loaded design NBR would have to be accomplished by the use of Load Sensitive Brake Equipment.

The amount by which the loaded design NBR could be increased using on-tread braking would have to be determined with wheel and brake shoe thermal capacity considerations as a factor. Depending upon the margin presently remaining in wheel and brake shoe thermal capacities, the use of disc-assist or other forms of braking might be necessary.

4.3.3.1 Load Sensitive Brake Equipment - Various forms of load sensitive brake equipment are in use in mass transit equipment in the United States and on mass transit, passenger, and freight equipment in Europe.

The various forms of load sensitive equipment differ greatly in their technical sophistication. Some require elaborate electronic subsystems that identify and correct wheel slip conditions; others provide the basic function of detecting the loaded or empty condition of the car and vary the NBR accordingly.

Load sensitive brake equipment can be generally divided into three main categories: (1) Load Limiting, (2) Empty-Load, and (3) Load Proportional.

1) Load Limiting. The purpose of load limiting equipment is to limit the brake cylinder pressure when a car that has a high loaded design NBR is empty. As applied to North American freight train braking systems, a load limiting device known as the L-1 Detector Valve has been proposed.

The L-1 Detector Valve limits brake cylinder pressure of an empty car to approximately 35 PSI regardless of the brake pipe pressure. The empty condition of the car is measured by truck spring deflection when the brakes are applied.

2) Empty-Load. The empty-load equipment provides

a full range of proportional control of any degree of service or emergency applications, but proportionalizes the brake application based on two separate levels of brake force depending upon whether the car is empty of loaded.

Typically, the empty car adhesion demand is very close to the maximum wheel/rail adhesion found for "bad rail". Thus, the empty car braking level cannot be increased because wheel slide would result. On the other hand, the adhesion demand for a loaded car is generally significantly below the available maximum wheel/rail adhesion. This means that the loaded car braking level can be increased (assuming wheel thermal capacity is not exceeded). The empty/load device provides for the increase in loaded car braking level, without increasing the empty car braking level.

Older types of empty-load equipment used either two brake cylinders (one for empty and one for load), or a special differential area brake cylinder. The newer types of empty-load equipment (designated the SC-1) use the conventional single area brake cylinder piston.

The SC-1 equipment produces a higher brake cylinder pressure for loaded cars. Compared to the L-1 Detector Valve, the brake cylinder pressure produced by the SC-1 is also a function of brake pipe pressure for both loaded and empty cars. This characteristic would be extremely desirable if the entire fleet were converted to empty-load equipment. By increasing only slightly the design loaded NBR and decreasing the design empty NBR, the present level of braking could be maintained. Then after the entire fleet had been converted to empty-load equipment, train braking levels could be increased by unilaterally increasing brake pipe pressures.

3) Load Proporational. In the strictest sense of the terminology, a load proportional device would maintain a constant NBR regardless of car weight.

However, because the use of truck spring deflection is not a reliable method of determining car weight, existing systems are only found on mass transit and few passenger cars, and the weight of these cars is gauged pneumatically by tapping into the air suspension systems. Because most freight cars are operated in either the empty or loaded condition, and do not have pneumatic suspension systems, the added complexities associated with the application of load proportional devices would greatly outweigh the benefits produced when compared to the empty-load equipment.

4.3.3.2 Alternative Forms of Brake Rigging - To produce and distribute higher braking forces to the wheels, alternative forms of brake rigging could be considered. This might be necessary because of the stress limitations on conventional [illegible] and the cylinder diameter limitations of truck-mounted [illegible]. Alternate forms of brake rigging could include, for example, pneumatic-hydraulic rigging. A rigging of this type is presently in use on the experimental articulated hopper car on the Chessie System. Other freight car truck arrangements might also be used, such as the use of clasp brakes on each wheel, or the introduction of three-axle freight car trucks.

As an alternative to producing and distributing higher brake rigging forces, it might be possible to increase further the coefficient of friction of brake shoes. This approach would also provide for a fast, simple method of increasing the braking level of the fleet if performed in conjunction with procedures to prevent wheel sliding of empty cars.

4.3.3.3 Wheel and Brake Shoe Thermal Capacity Limitations - If it is considered desirable or necessary to increase the freight train braking level, the thermal capacity limitations on wheels and brake shoes would have to be considered. A substantial amount of laboratory research has been performed over the past decade in this area. This research has resulted in a better understanding of the mechanics of stresses developed in freight car wheels from thermal and physical loading, and has resulted in a tentative limitation on the Brake Horsepower (BHP) versus Time curve for freight car wheels. This research tends to indicate that for typical freight train operations today, the most severe thermal loadings occur during grade-balancing drag braking, and that the tentative continuous limit for general types of operations is approximately 40 BHP (for a 33-inch wheel).

Because the power generated during drag braking operations is the product of the train speed and the retarding force produced by the brake shoe, the BPH per wheel can be kept low by operating trains at reduced speeds on long, descending grades. For example, a 13,000-ton train descending a 1.5 percent grade approaches the 40 BHP level at 50 mph.*

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* Blaine (1969).

It is important to note, however, that this assumes a considerable level of dynamic braking. Without the dynamic brake horsepower effects, 40 BHP per wheel would be generated at a much lower speed.

Higher braking levels produced by higher NBR's and train speeds would also have an effect on brake shoe wear. At the 15-BHP range, the brake shoe wear rate would be about one-half that of the 25-BHP range. At 35-BHP range, the brake shoe wear rate would be about double that of the 25-BHP range. (Blaine, 1969, p.4.)

The commonly accepted temperature limit to prevent accelerated (composition) brake shoe wear is approximately 600°F and occurs at approximately the 25-BHP per wheel level.

The thermal capacity limitations of freight car wheels, and the rate of brake shoe wear suggest that an increase in in freight train braking level might require other forms of braking. These forms might either supplement or completely replace on-tread braking of freight trains. Several alternative forms are discussed below.

## 4.4 ADVANCED TECHNOLOGY

A combined disc/on tread brake has been tested on a full-scale dynamometer by WABCO engineers using the disc brake applied to a 28-inch wheel. (Blaine, et al, 1969.) In these tests grade balancing was simulated by maintaining a constant 96-BHP/axle (48-BHP/wheel) loading for a period of one hour. The percentages of disc and tread braking were varied.

For the conditions tested the optimum balance between disc and tread temperatures was achieved at the 55 percent tread/45 percent disc distribution of BHP. In addition, it was estimated that this braking distribution would permit an improvement of approximately 100 percent in train operating speed and would cause a 34 percent increase in friction material wear costs.

The 55/45 distribution of tread/disc braking level was also used in performing stop distance tests. The average peak temperatures of the combined tread/disc brake were approximately two-thirds of the peak Fahrenheit temperature of the tread brake alone.

Other form of combination braking have also been proposed for freight operations. These include the "cheek" brake and the drum brake shown in Figures 4-2 and 4-3.

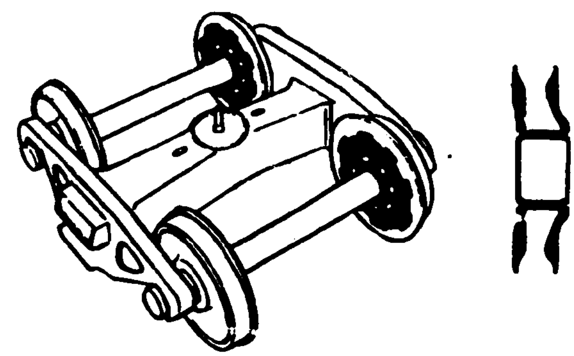

FIGURE 4-2

"CHEEK" BRAKE

Source: "Combination Friction Braking Systems for Freight Cars," Blaine, D. G., Cabble, G. M., Grejda, F. J., ASME Paper, Page 10.

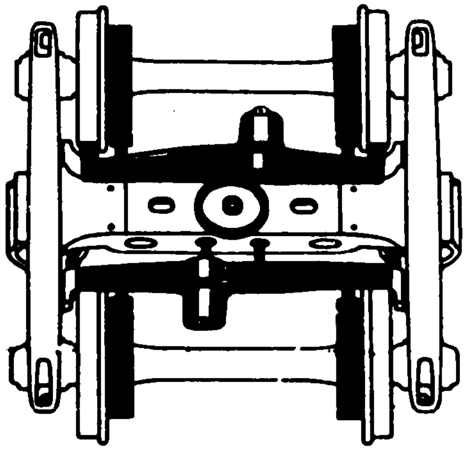

FIGURE 4-3

COMBINATION TREAD AND DRUM BRAKE

Source: "Combination Friction Braking Systems for Freight Cars," Blaine, D. G., Cabble, G. M., Grejda, F. J., ASME Paper, Page 10.

The cheek brake puts disc braking surfaces on either side of the wheel plate. This brake is used in limited numbers by the European and British railroads; however, it was considered doutbful by the researchers that it would have the energy absorption capacity for North American heavy grade operations. Probably its use also would require holes to be drilled through the wheel plate in order to secure it to the wheel. This would create wheel stress concentrations in the vicinity of the holes.

The combination tread and drum brake has also been proposed for use in North American rail freight operations. Conceivably such a design could utilize present styles of brake shoes and would not require major revisions to the brake rigging like that required for disc brakes.

The maintenance aspects of the various forms of combination braking would have to be investigated. Unless the supplemental brakes are mounted to the outside of the truck side frame, it would appear that the inspection and maintenance (shoes or placement) would be difficult.

### 4.4.1 The Disc Brake

The disk brake has been used in conjunction with on-tread brakes on passenger trains in the United States since 1955. However, disc brakes have not been used in freight trains in the United States. A comprehensive analysis of various disc brake designs was presented in a paper by a General Engineer of the French National Railway (S.N.C.F.) (Laplaiche, 1973). The author analyzed the behavior of disc brakes with respect to train stopping, train grade-balancing, and anti-skid requirements.

### 4.4.2 The Magnetic Rail Brake

The magnetic rail brake system, which can be used in conjunction with the normal air brake, acts directly on the track. However, because it is an "on-off" brake, it is normally used only for emergency applications.

The magnets of the magnetic rail brake are mounted between the two axles of the truck. While the train is moving the magnets are suspended above the track at a specified height.

The operation of the magnetic rail brake requires an electric circuit. When the circuit is closed the field coil of the magnet valve is excited and compressed air is allowed to enter operating cylinders and the magnets are lowered to the rail. The control current also permits operating current to flow into the brake magnetic coils, and the rail brake is fully effective.

### 4.4.3 The Eddy-Current Brake

The eddy-current brake consists of a series of electro-magnets which can be excited individually or in unison to provide a variable level of braking. The electro-magnets are mounted on a beam which is suspended from an unsprung portion of the truck. The lowering of the beam is performed by pneumatic actuators in conjunction with the operation of the normal air brakes.

The eddy-current brake requires a large amount of electric current for magnet excitation. This current could be produced by truck-mounted generators driven from an axle-mounted gear box.

The eddy current brake has been proposed primarily for high speed braking; the braking effort drops off rapidly for speeds below about 25 mph.

#### 4.4.4 Other Nonfriction Techniques of Braking

Other nonfriction braking techniques have been proposed for high speed railway vehicles. These have included air retarding, hydraulic retarding, and aerodynamic braking. Although these techniques might have application for high speed passenger operations in North America, they do not appear applicable for freight trains operated below 80 mph (Cassidy, 1971) because of their loss of effectiveness at low speeds.

#### 4.4.5 Devices to Assist in Train Handling

The operation of brakes on long freight trains is probably the most difficult aspect of train operation faced by the engineman. Train brakes are frequently used to control slack by "stretch braking" or "power braking" which is the simultaneous application of power (tractive effort) and brakes, to keep the train stretched (in tension). The control of slack over undulating terrain is essential for the prevention of destructive dynamic forces which can cause damage to equipment and lading, and can even produce derailments.

Freight train braking system operating characteristics are often cited as a primary cause of train handling problems. It is, however, the use of the train braking system for slack control that often represents the train handling problem. Unfortunately no other means exist to control slack short of either replacement of the existing coupling systems by a type having no slack, or by making a drastic reduction in train speed to the point of severely limiting the level of service.

Power braking can cause a considerable amount of fuel to be consumed and a decrease brake shoe and wheel life. The monitoring of a small sample of freight train operations has revealed that, depending on the terrain profile, power braking consumes on the order of 0.1 to 0.35 BHP-HR/mile, and shortens the life of brake shoes by 50 percent to 70 percent.* This reinforces the view that the train handling problems associated with the braking system are in reality problems associated with coupler and draft gear slack.

Solutions for improved train handling can take on a number of forms. Several of these are described below.

4.4.5.1 Slack Control - Slack between cars results from two sources: (1) free slack between couplers and (2) draft gear movement. Table 4-2 shows the amount of slack present in trains of different lengths.

TABLE 4-2

TRAIN SLACK VERSUS TRAIN LENGTH

| Train Length | Free Slack | Draft Gear Movement | Total for Train |
|---|---|---|---|
| 50 cars | 50" | 250" | 25' |
| 100 cars | 100" | 500" | 50' |
| 150 cars | 150" | 750" | 75' |
| 200 cars | 200" | 1,000" | 100' |

Source: "Track Train Dynamics to Improve Freight Train Performance," 82-122. Pages 2-93. Association of American Railroads.

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* Data acquired from interviews with air brake system professionals who sampled the use of power braking on seven Railroad freight trains operated on the Missouri-Pacific Railroad.

As shown in Table 4-2, the amount of slack present in a 150-car train can be as great as 75 feet. It can also be seen that the slack caused by draft gear movement represents approximately 83 percent of the total train slack.

Although it is generally conceded that free slack is required to start the movement of long trains without exceeding locomotive traction motor short-time current ratings, and that draft gear cushioning is required on freight cars during switching and humping operations, the question arises as to whether a different slack threshold might not assist in train handling, or whether some system to provide slack "lock-out" should be provided between cars in a train after the train is in motion.

Recent tests performed by a major draft gear manufacturer involving the operation of long-distance, high-speed unit trains showed that draft gear characteristics have a direct effect upon the frequency and magnitude of the slack action forces produced within a train.

Because it is doubtful that even the most sophisticated brake control system could completely eliminate slack action forces, further research into slack restricting or slack lock-out devices should be initiated.

4.4.5.2 Information for the Engineman - Information concerning the predicted or actual location and magnitude of in-train forces would be extremely useful for the training of enginemen. Several types of devices have been proposed to provide this information, and are described below.

Power Force Indicator. For test purposes, the Electro-Motive Division of General Motors developed in their control laboratory a system which monitors the electric currents in one traction motor of each locomotive in the consist. An electronic device in each locomotive then emits a current (10 milliamps max.) which is proportional to the drawbar pull in power or braking in dynamic brake. The summation of these currents is displayed in the lead locomotive. The purpose of this test was to develop an inexpensive and reliable system where 5 percent accuracy is adequate as an aid to the engineman. The device could produce the following advantages:

1. Drawbar ratings would be respected while starting the train, particularly a heavy train with mixed power.

2. The effect of units with different gear ratios in the consist would be revealed.

3. Units not producing power properly would be identified.

4. The full dynamic braking forces would be displayed.

Slack-Buff Indicator. The Slack-Buff Indicator uses sensors placed at selected coupler pairs within the train to indicate whether the couplings are in draft (tension) or in buff (compression).

This system, which was developed by J. Varbel of the Transportation Systems Center, transmits the information every 10 seconds from each location using battery-powered transmitters. A received-display, located in the lead locomotive, indicates buff or draft conditions by using color-coded lights.

Train Tonnage Profile. The Train Tonnage Profile is an information tool that provides a graphic illustration of the mass distribution of the train consist. Developed by D. D. Grisson of the Southern Pacific Transportation Company, the profile graph also contains train information concerning the number of loads and empties, train tonnage and length, the horsepower per ton ratio, and average tons per car.

Train Handling Indicator (THI). The Train Handling Indicator (THI) is a device mounted in the cab of the locomotive which presents to the engineer a moving visual display of the track and conditions ahead of the train and under the train as the train moves over the railroad.

The THI displays a continuous track profile utilizing polyester tape, scaled to two inches per mile while actually displaying a six mile segment.

The train length indicator is adjustable so the engineer can see the position of the train on the track profile at all times and can readily determine the grade and curvature under all, or any portion of the train.

### 4.4.6 Summary

The design braking level of the typical freight train has been deteriorating over the years because of the large influx of high capacity freight cars with high gross-to-tare ratios that just meet the minimum loaded Net Braking Ratio (NBR). The deterioration of the effective train NBR has been partially checked by supplementing train design braking levels with increasing brake pipe pressures and by the use of locomotive dynamic brakes.

Further increases in brake pipe pressure are not advisable with present equipment because of the increased proability of wheel slip on empty cars. Additional use of dynamic brakes is not considered feasible because of: (1) present limitations of the dynamic braking capacity of locomotives, (2) the adverse train-track dynamic relationships that could result, and (3) the reliability question raised by routine reliance upon dynamic brakes to provide a major portion of train braking effort.

Brake system performance should be improved from two aspects: response and braking level. Although better braking response would reduce train stop distances and in-train slack action forces, it would not improve grade balancing power. Increasing the braking level would both reduce stop distance and increase grade balancing power; if increased uniformly, it could also permit faster response by permitting an increased brake cylinder pressure buildup rate.

To prevent wheel sliding on empty cars, an increased level of train braking would have to be accomplished by resorting to the installation of a load sensitive devices on cars with high gross-to-tare ratios. If present levels of wheel and brake shoe thermal capacity cannot be exceeded on loaded cars, an increased level of train braking would have to be accomplished by off-tread techniques.

Several techniques of off-tread braking exist in mass transit and passenger train operations. Because of the physical characteristics of nonfriction type brake systems are such that their performance deteriorates rapidly below normal maximum freight train operating speeds, it is unlikely that non-friction types of brakes would be practical alternatives.

Several types of friction brakes have been demonstrated and appear promising. These include the combination on-tread/disc brake, the pure disc brake, and the use of axle-mounted drum brakes. For inspection and maintenance reasons, the preferred arrangement of such brakes would probably require them to be mounted outboard of the axle bearings.

Other methods of improving brake system performance include the use of remote locomotives in long freight trains. This solution could improve train handling characteristics and braking response time, but would not increase the braking level, assuming equivalent horsepower-to-ton ratios.

Other opportunities to improve train handling aspects include the provision of additional information concerning coupler forces through the train for the engineman to use in managing the operation of the train and as an aid in training. Several types of these devices have been proposed or tested.

## 4.5 CHARACTERIZATION OF INNOVATIVE CONCEPTS

It is the purpose of this section to provide a quantitative assessment of the above alternatives using the Train Operations Simulator (TOS) computerized simulation model developed by the Association of American Railroads (AAR).

The topics discussed in this section are listed below, and are presented in the order shown.

1. Performance Criteria,
2. Interpretation of TOS Results,
3. Evaluation of Concepts,
4. Summary.

#### 4.5.1 Performance Criteria

The criteria used to formulate and evaluate innovative brake system concepts were focused upon the performance implications of these concepts. Because economic criteria were not included in the scope of the study, the economic impacts of these concepts were not estimated.

As summarized in Table 3-1, the performance criteria associated with freight train air brake systems included (1) train stop distance, (2) grade balancing power available, and (3) coupler forces generated. These criteria are in turn affected by (1) brake system response characteristics and (2) the magnitude and uniformity of freight car braking levels produced in response to the control inputs. For example, train stop distance can be affected by both brake system response and braking level. Grade balancing power is affected primarily by the design braking level of the cars in the particular train. The coupler forces generated during braking can be affected by both brake system response and by the degree of uniformity of the design braking levels of individual cars as they are located throughout the train.

#### 4.5.2 Interpretation of TOS Results

The Train Operation Simulator (TOS) computer model developed by AAR was used to evaluate the innovative freight train braking system concepts formulated during the study. This model, which was developed in connection with the Track-Train Dynamics research program, was used by the Transportation Systems Center (TSC) to perform the evaluation of the alternative concepts. The TOS model simulates train operations over a mathematically represented terrain profile using specified train locomotive and car consists and characteristics. Braking subroutines are included in the model to represent the functional performance of various types of brake system components as they respond to control inputs.

The output results of the TOS model include the milepost location of the rear end and head end of the train, the speed limit and current speed, the locomotive throttle position and traction motor current, the brake setting including brake pipe and brake cylinder pressures throughout the train, the speed and magnitude of maximum draft or buff coupler forces being generated throughout the train, and the maximum L/V ratio being produced.

The interpretation of the results of the TOS model when used to evaluate alternative brake system innovations must be made with care. Although the results produced by the model for evaluating each innovative concept were in good agreement with those anticipated, there were several instances where maximum coupler forces were produced by the model at the instant, or a brief time after, zero train speed was achieved. This suggested that as the train approaches zero speed, either the model is inconsistent with actual coupler force generation, or the management of locomotive power and train air brakes as represented in the model would be performed much differently by experienced enginemen.

### 4.5.3 Concepts Simulated

Several innovative concepts were simulated by configuring the TOS model input and by modifying portions of the air brake operation subroutines of the model as a method of representing the particular concept being evaluated. A total of 12 simulation runs were performed to evaluate the innovative concepts. The results of the 12 simulations are summarized in Table 4-3 and are discussed below in terms of the concepts evaluated and the methods used to represent them.

4.5.3.1 Uniform Braking Level Throughout the Train - Several simulations were performed to evaluate the effects of uniform braking levels produced by individual cars throughout the train. As summarized in Table 4-3, computer simulation runs 1 through 10 provided information to perform this evaluation. These simulations are discussed below.

Location of Loads and Empties. Because loaded and empty cars exhibit substantially different design Net Braking Ratios (6.5 percent and 30 percent, respectively) the location of loaded and empty cars in the train could affect the train stop distance and coupler force generation. A comparison of runs Nos. 1 and 2 showed that placing loads in the rear caused the stop distance to increase by over 6 percent, substantially reduced the maximum coupler draft forces (from 320 kips to 26 kips), but increased the coupler buff forces (from 146 kips to 393 kips).

Uniform Design NBR (12 percent). Simulation runs Nos. 1 and 5 showed the effects that a uniform (12 percent) NBR on all locomotives and cars would produce. Although train stop distance increased by slightly more than 4 percent (loads in front) maximum coupler forces were reduced in draft from 320 kips to 92 kips,

TABLE 4-3

EVALUATION OF INNOVATIVE CONCEPTS USING THE TOS MODEL

| Run No. | Concept | Description of Conditions Simulated* | Stop Distance (Feet) | Stop Time (min:sec) | Average Deceleration Rate (MPHPS) | Maximum Coupler Forces Encountered During Stopping: Draft Kips | Draft Car No. | Draft Time | Buff Kips | Buff Car No. | Buff Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Base Line; FS | Nominal Brake System;Loads in Front | 5,016 | 1:44 | 0.50 | 330 | 55 | 1:40 | -146 | 26 | |
| 2 | Loads in Rear | Nominal Brake System;Loads in Rear | 5,333 | 1:47 | 0.49 | 26 | 5 | 0 | -393 | 55 | |
| 3 | Loads in Front; 2 Locos + 2 Helpers in Rear | Nominal Brake System;Loads in Front | 4,066 | 1:53 | 0.46 | 414 | 90 | 0:10 | -80 | 15 | |
| 4 | Loads in Rear; 2 Locos + 2 Helpers in Rear | Nominal Brake System;Loads in Rear | 4,224 | 1:29 | 0.58 | None | N/A | N/A | -364 | 53 | |
| 5 | 12% Uniform NBR (cars & locos) | Locos in Front;Loads in Front | 5,227 | 1:51 | 0.47 | 92 | 55 | 1:44 | -183 | 37 | |
| 6 | 12% Uniform NBR (cars & locos) | Locos in Front;Loads in Rear | 5,914 | 2:07 | 0.41 | None | N/A | N/A | -308 | 55 | |
| 7 | 12% Uniform NBR 2 Locos + 2 Helpers in Rear | Loads in Front | 4,382 | 1:38 | 0.53 | 70 | 53 | 0:11 | -103 | 55 | |
| 8 | 12% Uniform NBR 2 Locos + 2 Helpers in Rear | Loads in Rear | 4,541 | 1:35 | 0.55 | 24 | 104 | 0:04 | -71 | 53 | |
| 9 | 2%NBR; 10%LNBR (cars only) | Locos in Front;Loads in Front | 5,016 | 1:54 | 0.46 | 262 | 51 | 1:44 | -146 | 26 | 0:09 |
| 10 | 2%NBR; 10%LNBR (cars only) | Locos in Front;Loads in Rear | 5,491 | 1:40 | 0.40 | 26 | 5 | 0 | -383 | 55 | 1:47 |
| 11 | Base Line Emergency | Nominal Brake System;Loads in Front | 2,746 | 1:29 | 0.58 | 433 | 55 | 1:05 | -247 | 32 | 0:06 |
| 12 | Emergency; Instantaneous Signal | Nominal Brake System;Loads in Front | 2,587 | 1:15 | 0.69 | 431 | 55 | 1:05 | -74 | 2 | 0:01 |

* Nominal Conditions Simulated:

**Train:** 4 Locos (SD-40s), 100 Cars (50 loaded/50 empty), 1 caboose; Total Tonnage = 8,064 Gross Tons; Total Length = 5,802 Feet.

**Train Consist:** 50 132-ton cars, composition brake shoes, AB brake valves, MK 50 draft gear; 50 30-ton cars, cast iron brake shoes, AB brake valves, MK 50 draft gear; 1 20-ton caboose, cast iron brake shoes, MK 50 draft gear.

**Train Operation:** Initial speed 52 MPH, level grade, tangent track.

**Brake Operation:** Full Service (FS) Application, Initial Brake Pipe Pressure = 70 PSI, Initial gradient 1 PSI. no dynamic brake throttle at idle during braking.

but were slightly increased in buff from 146 kips to 183 kips. By placing the loads in the rear (run no. 6), the draft forces were completely eliminated, while the buff forces increased by 18 percent over base line.

Ten percent Loaded NBR; Twenty-Five Percent Empty NBR.

Because of wheel and brake shoe thermal capacity limitations of a single 12 percent loaded NBR car in a train with an average loaded car NBR of less than 8 percent, the loaded NBR of 10 percent is presently considered to be a maximum for on-tread braking. To increase the loaded NBR from 6.5 percent to 10 percent would require load sensitive equipment to retain or reduce the empty car NBR to prevent wheel sliding. Although the maximum empty car NBR could be retained at 30 percent, it is considered desirable to reduce the empty car NBR to approximately 23 percent to provide adequate margin to prevent wheel sliding on trains operated at high (over 70 PSI) brake pipe pressures.

Run No. 9 simulated a 23 percent empty NBR and a 10 percent loaded NBR on the cars only, with the loads in front. Compared to the base line run (run No. 1), the stop distance was identical, the maximum draft coupler forces decreased from 320 kips to 262 kips (20 percent), and the maximum buff forces remained the same (146 kips).

Run No. 10 was identical to run No. 9 except that the loads were placed in the rear. Compared to an equivalent baseline run (run No. 2), the stop-distance increased by almost 3 percent, the maximum draft coupler forces remained the same (26 kips), and the maximum buff coupler forces decreased from 393 kips to 283 kips.

The above results demonstrated that a more uniform net braking ratio can substantially reduce coupler forces and can provide a means to increase gradually the overall level of braking.

4.5.3.2 Faster Response - The effects of faster response times were evaluated using several methods. Faster response can produce shorter train stop distances and reduced coupler forces; however, it cannot increase grade balancing power.

Locomotive Location in the Train. Train brake system response can be improved by placing a portion of the locomotive consist back in the train. This has the effect of decreasing the effective train brake pipe length. Although several studies have indicated that the optimum position for remote locomotion locations is at the two-thirds position in the train, in the interests of simplifying the train operations the simulations were performed by placing two of the four units at the rear of the train.

A comparison of runs Nos. 1 and 3 showed that placing two of the locomotives in the rear reduced the stop distance by almost 20 percent, increased the maximum draft coupler forces from 320 kips to 414 kips, and reduced the maximum buff coupler forces from 146 kips to 80 kips. With the loads in the rear, distance was reduced by slightly more than 20 percent, maximum draft coupler forces were reduced from 26 kips (run No. 2) to zero, and maximum coupler buff forces were reduced from 393 kips to 364 kips.

Instantaneous Signal. The use of an instantanoues control signal like that which could be achieved using an electro-pneumatic system was stimulated for an emergency brake application by arbitrarily setting the signal transmission time to zero in the simulation model. The results are shown in runs Nos. 11 and 12. Compared to a base line simulation (run No. 11), the instantaneous signal reduced the stop distance by 6 percent, slightly reduced the maximum coupler draft forces from 433 kips to 431 kips, and substantially decreased the maximum coupler buff forces from 247 kips to 74 kips.

The simulation results demonstrated that a faster brake signal transmission speed can have favorable effects on train stop distance and coupler force generation. It should be noted also that an electro-pneumatic system would provide the opportunity to implement a graduated release feature for freight brake systems.

### 4.5.4 Evaluation of Results

The results of the concepts simulated are discussed below in terms of the brake system performance criteria previously defined: grade balancing power, train stop distance, and coupler forces generated.

4.5.4.1 Increased Grade Balancing Power - Because of the deterioration of the average train design NBR over the past 45 years, and because the methods of offsetting this decrease have been exhausted for all practical purposes, an increase in grade balancing power is necessary.

Load Sensitive Equipment. The grade balancing power required to balance the mass of a train consisting of 132 gross ton cars on a 2 percent descending grade can be calculated to be equivalent to a Net Braking Ratio of approximately 6.7 percent (neglecting train resistance); this means that, for a train operating with a 70 PSI brake pipe, a full service brake application would be required to balance the grade. Although increased brake pipe pressures (up to 90 PSI) and the use of locomotive dynamic brakes have provided adequate grade balancing power, if it is considered necessary in the future to increase grade balancing power by any appreciable amount, the loaded NBR would have to be increased separately to avoid wheel sliding on empty cars and to reduce the dependence on the reliability of locomotive dynamic brakes. In short, an increase in grade balancing power implies the introduction of load sensitive air brake system devices.

An increase in NBR could be achieved by increasing the minimum loaded design NBR from 6.5 percent to approximately 10 percent, and by decreasing the maximum empty design NBR from 30 percent to approximately 23 percent. This would provide an increased grade balancing power on loaded trains, would reduce the amount of wheel sliding of empty cars in a mixed train, would provide more uniform NBR's between empty and loaded cars (23 percent and 10 percent versus 30 percent and 6.5 percent), and would provide the opportunity to increase brake pipe pressure from 70 PSI in the future without causing wheel slide on empty cars in a mixed train. In addition to increased grade holding power, the simulation results have shown that the more uniform NBR would produce lower coupler forces during braking, and would produce shorter stop distances for loaded trains.

Load Sensitive Equipment Combined With Off-Tread Braking. Although it is generally conceded by the professionals in the industry that the above design NBR's would not exceed wheel and brake shoe thermal capacity limitations, a loaded design NBR of more than 10 percent is presently not considered to be a safe level with on-tread brakes. To increase the loaded NBR would require a supplementary form of off-tread braking, the use of six-wheel trucks, or other means of increasing the braking level without exceeding a 10 percent loaded NBR on the wheel tread.

Assuming this additional braking capacity could be achieved, the loaded NBR could hypothetically be made equivalent to the empty car NBR in the vicinity of the 23 percent value, depending upon the magnitude of brake pipe pressures used. This would provide the maxium utilization of available wheel/rail adhesion, and produce a completely uniform train NBR. Train grade balancing power would be substantially increased, train stop distance would be greatly shortened, coupler forces would be reduced, and train handling would be consistent for loaded and empty trains.

4.5.4.2 Decreased Train Stop Distance - Train stop distance can be decreased by increasing the NBR as discussed above and by decreasing the response time of the brake system. The response time can be decreased by using remotely controlled locomotives or air brake repeater units placed throughout the train. Simulations have indicated that faster control signal transmission rates can reduce stop distances on the order of 10 percent. Remotely controlled locomotives also tend to reduce brake pipe leakage problems and contribute to better train handling in general.

Faster control signal transmission speeds could also be accomplished by providing an electro-pneumatic brake system. They could also provide the opportunity to introduce graduated release response.

4.5.4.3 Reduced Coupler Forces - Reduced coupler forces could be achieved by providing more uniform NBR's throughout the train and by increasing the speed of control signal transmission.

Although the position of loaded and empty cars in a train affects the magnitude and location of coupler forces during braking, simulation results indicate that the best arrangement of loads and empties for a full sevice brake application is not necessarily the best arrangement for an emergency application. In addition, there are severe operating problems in sorting cars not only by destination but also by weight.

Draft gear characteristics have also been shown to have a direct effect on train coupler forces. Further research into this area is recommended to determine the most benefits in terms of reduced coupler forces.

4.5.4.4 Sumary of Results - The TOS simulations performed by the Transportation Systems Center have produced the results shown in Table 4-4.

TABLE 4-4

CHARACTERIZATION OF INNOVATIVE BRAKING CONCEPTS

| Concept | Method of Implementation | Performance Benefits |
|---|---|---|
| Increased loaded NBR; make train NBR more uniform | Load sensitive equipment | Increased grade holding power<br>Reduced wheel sliding<br>Shorter stop distances<br>Reduced coupler forces |
| Faster transmission speeds | Remotely controlled locomotives | Shorter stop distances<br>Faster brake release<br>Fewer leakage problems<br>Better overall train handling (including reduced coupler forces during braking) |
| | Electro-pneumatic system | Shorter stop distance<br>Reduced coupler forces<br>Graduated release capability |

# 5. CONCLUSIONS

## 5.1 INTRODUCTION

The objectives of this project included the development of conclusions concerning two areas:

1. Improvements and/or innovations to minimize current problems with freight car braking systems which affect train braking performance.

2. Long-Range substantive changes and research activities intended to result in systems which improve freight train braking performance.

Based upon the findings of the project, which include the views and judgments of the members of the railroad and supply industries, as well as the collective assessments and judgments of the project team, several conclusions have been developed and are presented in this section.

To present the rationale behind the conclusions, this section first includes a summary of the performance of existing freight train braking systems, and a statement of the performance-related objectives of an improved braking system. These topics are followed by a presentation of the short- and long-term suggested actions.

## 5.2 SUMMARY OF FREIGHT TRAIN BRAKING PERFORMANCE AND TRENDS

The performance of freight train braking systems can be discussed from the four perspectives presented on the following:

1. Performance of Freight Car Braking System Components,

2. Braking Performance of Freight Train,

3. Trends in Braking Performance,

4. Trends in Innovation.

### 5.2.1 Performance of Freight Car Braking System Components

From the standpoint of freight train braking performance, the most sophisticated brake system component of a freight car is the brake control valve. This valve, which senses pneumatic pressure signals from the single train brake pipe, has been refined considerably over the past 50 years. The present day brake valve will ultimately improve train braking performance. However, these improvements, while important, are not revolutionary. Furthermore, it is an accepted fact that practical limitations in brake valve sensitivity have been reached assuming continued long, heavy train operation and continual use of a single pneumatic brake pipe as the only form of brake system communication.

### 5.2.2 Braking Performance of Freight Trains

The braking performance of freight trains has been measured both empirically and by computer modelling. The results show that large variations in freight car deceleration rates occur within a train during brake application. These variations occur primarily because of the serial action of the braking communication characteristic of long brake pipe of long trains, and the ultimate nonuniformity of braking force levels produced throughout the train by the single capacity brake system of each freight car.

Brake release also represents a problem. As in brake application, the release signal propagates serially through the brake pipe but, compared to brake application, which can be made in small increments, a brake release can only be performed in a singular, complete-release mode.

### 5.2.3 Trends in Braking Performance

In the past, it was possible to design the braking system of a freight car to produce higher loaded net braking ratios without incurring wheel slide when the car was empty. With the more recent introduction of high gross-to-tare ratio cars, the loaded net braking ratio had to be reduced to prevent empty car wheel sliding. As a result, the overall braking performance of the entire North American freight car fleet, as measured by loaded NBR, is deteriorating. This trend has been offset by increased reliance on locomotive dynamic brakes and increased brake pipe pressures; however, the benefits that these measures can produce have been, for all practical purposes, exhausted. If not reversed, this trend implies longer train stop distance and reduced grade holding power in the future.

While many of the above limitations of freight train braking would become less significant if the railroad industry were to operate shorter, lower tonnage trains at reduced speeds, it is the consensus of the project team that this is unlikely to occur. Indeed, continuation of present trends will impose even greater demands on the braking system. In essence, the performance problems of today could be magnified in the future, and will not be solved unless several types of improvements are made.

### 5.2.4 Trends in Innovation

The brake system improvements and innovations that have been implemented or proposed for implementation have characteristically been introduced by the brake system component suppliers. Several "on-the-shelf" innovations are presently available as the result of the highly capable research and development efforts of the suppliers. However, the economics or regulatory necessities of introducing these innovations have not been clearly quantified or defined. As a result, the suppliers of air brake system components are presently uncertain as to the preferred direction of further research and development efforts.

## 5.3 OBJECTIVES OF AN IMPROVED FREIGHT TRAIN BRAKING SYSTEM

Operational characteristics of improved freight train braking systems and components, which can be fully implemented within twenty years, have been defined. The features of such an "ideal" brake system would include:

A. Instantaneous, fully-graduated brake application and release throughout the train and

B. Higher and uniform braking levels developed throughout the train.

The benfits that would result from the above two features would include the following:

1. <u>More predictable train stop distance</u>. Train stop distances would become more predictable because uniform braking levels throughout the train would produce consistent deceleration rates regardless of the mix of loaded and empty cars. Furthermore, the instantaneous, fully-graduated brake application and release feature would permit the engineman to "trim" the deceleration rate with substantially greater precision.

2. Improved train speed control. Train speed control would be improved by virtue of uniform braking levels and instantaneous, fully-graduated brake application and release. As compared to the present braking system, the release could be made in graduated increments, providing the engineman to alternately make small adjustments in brake application and release in order to control speed while the train is operated over undulating track profiles.

3. Shorter stop distance. A shorter stop distance would result by virtue of higher braking ratios, and from faster brake application response.

4. Increased grade balancing power. Grade balancing power would increase by virtue of increased braking ratios, which could be realized by more uniform development of braking levels throughout the train.

5. Reduced train dynamic forces during brake application and release. Train dynamic forces during brake application and release would be reduced by virtue of uniform braking levels throughout the train and by virtue of an instantaneous brake signal transmission.

6. Elimination of undesired brake application due to pipe pressure perturbations. The use of an instantaneous brake transmission signal to control brake application and release would eliminate the dependence upon the single, penumatic brake pipe for brake system communications. Consequently, small pressure perturbations in the brake pipe would not be interpreted as brake application commands by freight car control valves.

7. Elimination of wheel sliding on empty cars. The empty cars of present day mixed freight trains operated down severe grades using high brake pipe pressures experience wheel sliding under large brake applications. A braking system that distributes the braking levels uniformly among loads and empties would eliminate the wheel sliding of empty cars.

8. Negation of the problems of blocking loads and empties. In an effort to reduce train dynamic forces during brake application, it has been recommended that loaded and empty cars be blocked in a train when practical. A more uniform, instantaneous brake system would negate this problem.

The above benefits are not all-encompassing. Several additional benefits would also result indirectly. These would include reduced lading damage and reduced freight car repair expenses.

## 5.4 POTENTIAL MEANS OF IMPROVEMENT

The technical feasibility, operational practicality, and economic viability of the many possible means of improving brake system performance cannot at present be determined with any real certainty. However, this study has resulted in the identification of a number of potentially beneficial steps. They are presented here with the understanding that considerable further research, development, and testing would be required to permit firm conclusions as to the most practical and cost-effective course to be followed. These findings have been divided into two categories: improvements that could be implemented in the short-term (within 10 years) and research that would have to begin now for improvements to be implemented in the long-term (within 20 years).

### 5.4.1 Short-Term Improvements (Implementation Possible Within 10 Years)

1. Install empty-load equipment on all new cars with greater than a specified gross-to-tare ratio, for example 2:1. This empty-load equipment must have provisions for making separate field adjustments for setting the empty and loaded braking levels.

2. Install empty-load equipment on existing cars of greater than a specified gross-to-tare ratio, for example 3:1. Include separate field-adjustable settings for the empty and loaded braking levels.

3. As an initial setting, adjust the loaded net braking ratio at approximately 10 percent, and the empty net braking ratio at approximately 25 percent, based upon current specifications for high friction organic brake shoes.

4. Install on all new cars brake rigging that provides uniform braking levels on all wheels of the car during all stages of braking.

5. Install a variable-limit pressure limiting valve to limit brake cylinder pressure to a pre-set value (for example, 50/60 psi) for both full service and emergency brake applications.

6. Standardize train brake pipe pressures at approximately 110 psi. This should follow the completion of all cars being equipped with brake cylinder pressure limiting valves. The

combined use of brake cylinder limiting valve and head-end setting of 110-psi brake pipe pressure would provide a 100% improvement in brake pipe gradient versus the present 80-psi brake pipe pressure with an allowable 15-psi gradient.

7. Examine alternative approaches for inspecting and testing train brake systems. The inspection and testing of freight train air brake systems requires substantial amounts of time and resources. An investigation should be made concerning the need for the present inspection and testing practices and procedures. The study should include the feasibility of introducing alternative means or intervals for inspection and testing of air brake systems without jeopardizing safety and reliability. One method for inspection and testing might include variable degrees of automation or an innovative inspection schedule. For example, it might be possible to remove a numerical series of cars from service (such as car numbers ending in a certain digit) during a particular month to perform a thorough mechanical inspection. With realistic provisions this procedure would enable the owner to schedule the car to a suitable, and perhaps a more efficient, shop when the car is empty or in storage.

A thorough mechanical inspection schedule might result in longer periodical attention intervals. Moreover, performing the inspection at specified shops would alleviate AAR billing and would appreciably reduce stock inventory.

8. Improve the end-of-car arrangement. Problems with the air hose coupling, the uncoupling lever and coupler arrangement were most frequently cited as the major problems of the air brake system by the railroads. It is recommended that end-of-car problems be examined using an engineering approach. For example, it might be possible to develop an entire end-of-car structural component that would include the draft gear, coupler, air hose and uncoupling mechanism as a single module.

9. Improve the "fail safe" characteristic of the air brake system. The present air brake system has been described as being "fail safe" or "automatic." This terminology is used to describe the operating mode in which the train brakes will automatically make an emergency application in the event that the train separates while in motion. However, if an obstruction in the train brake pipe occurs after an initial brake inspection is made, the braking capacity of the train could be drastically reduced, depending on the location of the obstruction in the brake pipe. It is therefore recommended that an automatic emergency brake application also occur if the local brake pipe pressure drops below a certain pre-set value, such as 40 psi. This would provide protection against brake pipe obstructions (such

as closed angle cocks).

5.4.2 Long-Term Improvements ( Implementation Possible Within 20 Years)

1) New Freight Car Brake Control Valve. Develop a lightweight, electro-pneumatic control valve that would be compatible with existing control valves during the interim period, but would eventually be easily modified to incorporate the following features:

a) Provide a fast charging system (two pipe system may be required - brake pipe and supply line).

b) Provide a sufficient supply reservoir volume to insure at least three (3) full service applications in succession.

c) Provide satisfactory brake operation with at least 110-psi brake pipe pressure.

d) Provide that all brake control valves in the train instantaneously respond to brake control inputs.

e) Regulate brake cylinder pressure development to approximately three-pound pressure increments with each one-pound reduction in brake pipe pressure.

f) Provide a pressure limiting valve (58-60-psi) to limit the brake cylinder pressure on each car such that the braking forces produced do not exceed the established empty car wheel-to-rail adhesion limit.

g) Provide controlled brake cylinder pressure reduction in three-pound increments from 60-psi to exhaustion.

h) Provide automatic built-in test apparatus on each car for purpose of testing the electro or pneumatic components of the braking system.

i) Develop an annunicator to indicate that the train brakes have been applied effectively. Examine the feasibility of employing an automatic scanner either on board the train or located along the wayside for the purposes of making car-to-car brake tests.

j) Provide a brake valve feature on each car to initiate an emergency brake signal in the brake pipe when brake pipe pressure drops to a low value, approximately 40-psi. This would provide protection against brake pipe obstruction.

2) New Truck Component Design. New truck design should incorporate the following features:

a) Larger diameter wheels with improved metallurgical properties to reduce wear and increase thermal capacity.

b) Supplementary off-tread brakes as an assist to the on-tread brakes.

c) Long-life brake shoe materials to reduce inspection requirements and maintenance costs.

d) Highly efficient brake rigging providing uniform braking levels on all wheels and/or discs during all stages of brake application.

3) Rail Adhesion Values. Define and establish guidelines that will govern minimum adhesion levels for freight car braking in a freight train during normal operation.

4) Load Compensating Equipment. Develop improved load compensating brake equipment that will respond to actual weights, will not exceed established thermal capacities of brake shoes or wheels.

5) Brake System Component Research. Research should be continued to develop improved wear and performance characteristics of brake system components. The research should include, but not be limited to, the following:

a) Analysis of brake shoe and wheel frictional and wear characteristics. The analysis should be made for various types of brake shoes used in conjunction with different classes of freight car wheels with the objective of maintaining uniform frictional characteristics at all speeds, including static conditions. The expected brake shoe and wheel wear rates should also be quanitified.

b) Assessment of the thermal and physical capacities of wheels and brake shoes. Although a substantial amount of research has been performed to assess the thermal capacity of freight car wheels with respect to on-tread braking, additional research efforts appear to be warranted to assess the combined physical and thermal capacities of different classes of freight car wheels subjected to on-tread braking by various types of brake shoe materials, including the high-phosphorus content metal brake shoe.

6) <u>Automatic Couplers</u>. Develop automatic couplers with increased gathering range, automatic angle cock, and provisions for making mechanical, pneumatic, and electrical connections automatically.

7) <u>Draft Gear</u>. It is a curious fact that, on the one hand freight train brakes are used routinely to control train slack action, and on the other hand, the brake system is alleged to create serious slack action forces during brake application and release. Preliminary estimates indicate that in certain territories "power braking" consumes up to half of the brake shoe life, and increases locomotive fuel consumption. The results of research performed by at least one manufacturer of draft gear have demonstrated that train slack action forces can be directly affected by draft gear characteristics. It is therefore recommended that an investigation of the characteristics and condition of in-service draft gear and coupler assemblies be performed, and that the sensitivity of train slack action forces to draft gear characteristics be quanitified.

8) <u>Train Communications System</u>. Research should be continued to determine the benefits of providing the engineman with additional inputs and control capabilities with the objectives of simplifying the management of train operation and improving safety. A train communications system should be developed for the purpose of providing the engineman with in-train coupler force information, to control remote locomotive units, to perform train brake testing, and to provide a variety of functions to assist train operations, such as monitoring journal temperatures, wheel lift-off, or other conditions related to causes for derailment.

9) <u>TOS Model</u>. Continued research should be conducted to evaluate and test, where appropriate, innovative braking system concepts. The TOS simulation model appears to represent an extremely useful tool to perform the parametric analyses necessary to evaluate selected innovations. To assure meaningful results, the internal structure of the model should be reviewed to verify its limitations, and realistic control inputs should be input to the model by those experienced with actual freight train operation.

## APPENDIX A - GLOSSARY OF TERMS

AB Valve (Including related valve schedules such as ABD, ABDW and Z1A) - The pneumatic control valve on each car that controls the brake operation of the car.

Accelerated Emergency Release - A brake release feature where each car assists in recharging the brake pipe by permitting emergency brake cylinder pressure to flow into the brake pipe for the initial portion of the brake pipe recharge.

Accelerated Service Release - A brake release feature designed into the ABD brake valve which functions to assist brake pipe recharging after a service application by permitting air under pressure from the emergency reservoir of each car to flow into the brake pipe.

Adhesion - The coefficient of friction between the wheel and the rail. Normally expressed as a percentage in terms of maximum tractive force of a rail vehicle divided by its gross weight.

Air Brake System - All of the devices and components included on a train that can act to limit train speed.

Air Hose - A flexible hose attached to the end of the brake pipe on each car which is manually connected to a mating hose of an adjacent car to form an effectively continuous brake pipe.

Air Reservoir - A twin compartment (auxiliary and emergency) tank mounted on each freight car that stores compressed air for use in brake applications.

Angle Cock - A manually operated valve located at each end of locomotives and cars used to open or close the brake pipe.

Automatic Air Brake - An arrangement of brake equipment which stores energy for brake application. For the standard air brake system, the braking energy is stored as compressed air in reservoirs on cars and locomotives. A reduction in brake pipe pressure from whatever cause, tends to cause a brake application. An increase in brake pipe pressure tends to release the brakes.

Automatic Brake Valve - A manually operated device on the locomotive which can be positioned by the engineman to: (1) control the flow of air into the equalizing reservoir and brake pipe for charging them and releasing a brake application, and (2) provide a reduction of equalizing reservoir and brake pipe pressures to effect a service or emergency rate of brake application.

Automatic Slack Adjuster - An appliance to restore automatically the brake cylinder piston travel to a predetermined distance and thereby, compensate for brake shoe wear.

Auxiliary Reservoir Compartment - A storage volume for compressed air which is charged from the brake pipe and which provides air pressure for use in service and emergency brake applications.

"B" End of Car - The end of a freight car on which the hand brake assembly is located.

Bleed or "Bleed Off" - A term commonly used for the venting of air pressure to the atmosphere, as in the venting of the air pressure from the brake cylinder of air reservoir of individual cars by manual manipulation of a release valve. The operation of the release valve depends on the type of brake equipment installed on the car.

Brake Beam - A structure located on the freight car truck that transmits the braking force from the brake cylinders to the wheels.

Brake Cylinder - A cylinder within which compressed air from the air reservoir acts on a piston which transmits the force of the compressed air to the associated brake rigging which in turn forces the brake shoes against the wheels.

Brake Cylinder Release Valve - A manual device for quickly releasing the air from a brake cylinder without depleting the air stored in the reservoir on the car. This action is called bleeding.

Brake Hanger - The part of the foundation brake rigging that holds the brake head or beam in position.

Brake Head - A holder attached to or a part of the brake beam which carries the detachable brake shoe.

Brake Pipe (Train Line) - The interconnected air brake piping of cars and locomotive(s) which acts as a supply pipe for the reservoirs on each car and is the sole connecting means by which the train brakes are controlled by the locomotive engineman. Flexible air hoses provide connections between the cars. When a train is made up and all air hoses are connected, the entire pipeline comprises what is commonly called the brake pipe.

Brake Pipe Gradient - A term used to express the difference between air brake pipe pressure at the head-end and rear-end of a train.

Brake Pipe Pressure - The pressure of the air in the brake pipe expressed in pounds per square inch.

Braking Force - The total force (in pounds) pressing the brake shoes against the wheels.

Braking Power - A term used to describe the ability to either control train speed on a descending grade, or to bring a moving train to a controlled stop.

Braking Ratio - The ratio obtained by dividing the total braking force between the brake shoes and the wheels by the weight of a car or locomotive. It is usually expressed as a percentage value. Gross braking ratio is the ratio of the theoretical (without efficiency losses) total brake shoe force divided by the car weight in its loaded or empty condition. Net braking ratio includes efficiency losses of the rigging and is the (actual) brake shoe force divided by the weight of the car.

Brake Shoe - A replaceable friction element secured to the brake head for the purpose of producing a retarding force when forced against a wheel tread.

Brake Shoe Key - A key by which a brake shoe is positioned and fastened to a brake head.

Brake Shoe Force - The total force in pounds exerted by the brake shoe on all wheels when the brakes are applied.

Brake System - Includes all brake apparatus working harmoniously on railway vehicles. (Same as Air Brake System.)

Buff - Compressive coupler forces.

Center Sill - The central longitudinal member of the underframe of a car which transmits longitudinal forces from one end of the car to the other.

Clasp Brake - A brake arrangement having two brake shoes per wheel.

Control Stand - The upright column to which the locomotive throttle control, reverser handle, transition lever and dynamic braking control are mounted in a locomotive cab within convenient reach of the engineman. Air gauges and some other control switches are also included on the control stand.

Cyclic Braking - A term used to describe the alternative brake application and release used by the engineman to control slack-action forces when operating trains over undulating terrain.

Direct Release - The normal total release functioning of freight car brake equipment. When the control valve is moved to release position by increasing brake pipe pressure, brake cylinder pressure is exhausted, thereby removing the retarding forces.

Draft - A term used to describe tensile coupler forces.

Draft Gear - A shock cushioning unit installed at each end of a car or locomotive, to which the coupler is attached, which transmits compression (buff) and tension (draft) forces between the coupler and the center sill of the car or locomotive. The draft gear is within the coupler yoke.

Driver - A locomotive wheel connected to the propulsion system capable of providing tractive effort.

Dynamic Brake - Dynamic braking is an electrical means used to convert some of the energy of a moving train into an effective retarding force by causing the traction motors to function as generators, the energy so generated being dissipated as heat from resistors.

"Dynamiter" or "Kicker" - A slang term for a car with a defective brake valve which spontaneously creates an emergency brake application throughout the train. Common causes are stuck control valve, or the opening of these valves due to the vibration and/or slack-action of the car.

Emergency Application - A rapid exhausting of air pressure from the brake pipe which exceeds the service rate of reduction and trips the brake pipe vent valves on each car, resulting in a controlled stop of the train in the minimum safe distance.

Emergency Reservoir Compartment - A storage volume of the air reservoir for compressed air to provide air pressure for use in emergency brake applications and for certain recharge features (for example, accelerated service release feature of ABD valve).

End-of-Car Cushioning Device - A unit installed at both ends of a car for the purpose of absorbing energy through a hydraulic piston arrangement supplemented by springs. These are used to minimize or prevent damage to lading.

Equalizing Reservoir - A small reservoir on the locomotive which is connected to an equalizing piston of diaphragm chamber for use in automatic air brake applications. The equalizing reservoir lends stability by drawing air at a controlled rate from the brake pipe.

Failsafe - A term used to describe the characteristic of the braking system in which a train separation can cause an emergency brake application automatically.

Feed Valve (Regulating Valve) - The valve that reduces air pressure from the reservoir of the locomotive to the pressure desired in the brake pipe. The valve automatically maintains that pressure when the automatic brake is in running position.

Flat Spot - Loss of roundness of the tread of a railroad wheel caused by wheelsliding. Also called a "Slid-Flat."

Foundation Brake Rigging - The levers, rods, brake beams, etc., by which the piston rod of the brake cylinder is connected to the brake shoes in such a manner that when air pressure forces the piston out the brake shoes are forced against the wheels.

Full Service Application - A term used to define the application of the automatic air brake to the point that the auxiliary and brake cylinder pressures are equalized. This is the normal method of stopping a train.

Graduated Release - A feature designed into brake equipment, whereby brake cylinder pressure may be reduced in steps proportional to increments of brake pipe pressure buildup. This feature is not used in North American rail freight operations.

Hand Brake - An arrangement of levers, rods, and gears which are actuated manually to force the brake shoes against the braking surfaces to hold a car stationary.

Hot Journal Detector - A wayside located device that monitors the axle bearing temperatures of a passing train.

Independent Brake Valve - A brake valve that provides independent control of the locomotive brakes regardless of the automatic brake valve handle position.

Lever Ratio - The mechanical advantage obtained through a system of levers; generally in air brake practice, the ratio of the braking force pressing shoes against the wheels to the cylinder force.

Live Levers - Levers not having fixed or nonmovable connection at any point.

L/V Ratio - Defined as the ratio of the lateral force to the vertical force of a car or locomotive wheel on a rail. It is an important indicator of wheel climb, rail turnover and/or derailments.

Main Reservoir - A reservoir on the locomotive for storing and colling compressed air.

Net Braking Ratio - (See "Braking Ratio.")

Overcharge - A condition wherein car air reservoirs have been charged to a high brake pipe pressure, and then placed in a train operated at a lower pipe pressure, thereby preventing the brakes from releasing.

Over-Reduction - A service brake pipe reduction to a pressure lower than that at which the reservoir and the cylinder equalize.

"P" Wire - An electronic system controlling braking in a electro-pneumatic brake system.

Power Braking - A term used to describe the operation of a freight train in which locomotive power is used in conjunction with light train brake application to stretch the train and control slack-action. Also called "stretch braking."

Pressure Maintaining Feature - A system designed to overcome normal brake pipe leakage and maintain the brake pipe pressure at the desired level during a service reduction.

Pressure Retaining Valve - (See "Retaining Valve.")

Propagation - The serial action of transmitting a brake application from car to car through a train, such as in quick action, emergency or quick service.

Quick Action - The feature whereby the emergency brake pipe reduction is passed rapidly from car to car throughout the train.

Quick Service - A feature which provides a controlled service rate of brake pipe reduction through a local reduction of brake pipe pressure at each car.

Quick Service Limiting Valve - A portion of a brake valve that nullifies further quick service activity when the brake cylinder or displacement reservoir pressure reaches approximately 10 psi.

Quick Service Valve - A device auxiliary to the brake valve to assist in reducing brake pipe pressure, providing continuous quick service regardless of brake cylinder or displacement reservoir pressure. Each brake pipe reduction will cause the quick service valve to respond.

RCE-1 Unit - A locomotive unit or consist placed in the rear of the train and operated remotely, usually by radio link.

Reduction (of the brake pipe) - A decrease in brake pipe pressure at a rate and of an amount sufficient to cause a train brake application to be initiated or increased.

Reduction Relay Valve - A combination of an emergency vent valve and a continuous quick service valve mounted on a common pipe bracket, and designed for application to long freight cars to offset the effect of the increased volume and length of brake pipe per car by promoting quick service activity as well as ensuring the transmission of an emergency application through a train of long cars.

Release Rod - A small rod situated at the side sill of a car, for the purpose of manually releasing the air brakes at terminals to allow switching. (See "Bleed.")

Remote Consist - Designation for a locomotive consist and RCE-1 radio equipment that is placed in the body of a train and is controlled via radio by the engineman in the lead locomotive (or control) consist.

Remote Control Car (RCC) - A vehicle usually a locomotive shell or box car in which the remote RCE-1 equipment is installed. The RCC is then connected in multiple-unit mode to the motive power of the remote consist to control its operation. Both the RCC (if one is used) and the remote motive power make up the remote consist.

Remote RCE-1 Radio Equipment - Electrical equipment used to translate radio commands into control operations and to telemeter the status of the remote consist to the control unit. This equipment is permanently installed in either a remote control car, or a remote locomotive.

Retaining Valve - A manually operated valve through which the brake cylinder air is exhausted completely or a predetermined brake cylinder pressure is retained during the brake "release."

Rigging - The system of rods and levers which amplify and transmit the braking force from the brake cylinder to the brake shoes of a car.

Running Release - Release of a service application while the train is in motion.

Service Application - A gradual reduction of brake pipe pressure at a rate and amount sufficient to cause the brake valve to move to service position.

Service Brake - A brake application at a service rate and limited to a brake cylinder pressure less than emergency; i.e., the normal train stopping condition.

Service Rate - The rate, slower than emergency, which the brake pipe pressure reduces to cause the brake valves to assume service position.

Slack - There are two kinds of slack: One is termed "free slack" and is the accumulation of clearances and wear in the associated parts of the couplers. The other type of slack is called "spring slack" and results from extension of the draft gears.

Sliding Center Sill Cushioning Devices - Equipment installed between a fixed center sill and an auxiliary sliding sill that absorbs shock to the car. The sliding sill travels longitudinally through the fixed sill and acts as a single unit throughout the car.

Split Reduction - A term used to describe the process of making an initial brake pipe reduction to a lesser degree than the fully desired reduction, followed by further reductions until the desired total amount is reached. A smoother slowdown or stop is the principal advantage of this method, if properly performed.

Stretch Braking - (See "Power Braking.")

Tare Weight - The weight of the empty car.

Thermal Cracking of Wheels - Cracks in a railroad wheel due to excessive heat.

Tons per Operative Brake - The gross training tonnage of the train divided by the total number of cars having operative brakes (typically, 100%.)

Undesired Emergency - That situation whereby the train brakes apply in emergency (air brake application) from causes other than the engineman's actions. (See also "Dynamiter.")

Undulating Terrain - A track profile with grade changes such that a train passing over the track has some cars on three or more alternating ascending and descending grades.

Vent Valve - The name applied to a valve or valvular portion of a car or locomotive brake system which responds to an emergency rate of reduction of the brake pipe and in turn vents the brake pipe locally at each vehicle, thereby propagating serially the emergency application throughout the train.

Yard Plant - A system of piping and fittings installed in a classification yard between the tracks to provide an air supply at convenient locations for charging and making tests on cars without a locomotive being present.

## APPENDIX B - REFERENCES AND BIBLIOGRAPHY


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## APPENDIX C - REPORT OF INVENTIONS

This report includes a survey and assessment of present railroad freight train braking systems, evaluates brake system innovations, and presents conclusions which represent improvements that could be made within both the short term and the long term.

Section 2 presents a summarized historical preparation on the development of freight train and brake systems. This section includes a discussion of market entry, industry regulations, and governmental regulations which represents a new contribution.

Section 3 characterizes existing freight train braking technology. In particular, this section includes life cycle cost estimate of the population of air brake system components in service which represents previously unavailable information.

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