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EVALUATION OF CRITERIA FOR TRUCK AIR BRAKE ADJUSTMENT

INTERIM REPORT

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16. Abstract

This report presents analyses, findings and recommendations concerning the out-of service (OOS) brake adjustment criteria in the Federal Motor Carrier Safety Regulations and the North American Uniform Driver-Vehicle Inspection Criteria for heavy trucks.

The study involved interviews with MCSAP inspectors, reviews of recent studies of the influence of brake adjustment and preparation of documents on pertinent mechanical properties of S-cam brakes, mechanical analyses of stopping capability, statistical analyses of inspection data, and combined mechanical and statistical analyses for evaluating OOS criteria using detailed inspection data.

Several findings and recommendations are presented in the report. These include:

- Brake adjustment is most important at heavey loads and high brake temperatures in emergency stops on good roads. Results for stops from 60 mph at 400°F and full load on a high friction road are appropriate for comparing the influences of brake adjustment on stopping capability.
- The current system for assigning brake demerits using the 20 percent defective brake rule provides a reasonable separation between vehicles that are OOS and those that are not.
- Backed-off brakes should be given more attention in the OOS criteria. Perhaps a backed-off brake should be counted as 1.5 or 2.0 brakes in the 20 percent calculation.

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EXECUTIVE SUMMARY

The purpose of this Executive Summary is to describe analyses, findings, and recommendations concerning the out-of-service (OOS) brake-adjustment criteria as contained in Appendix B of the North American Uniform Driver-Vehicle Inspection Out-of-Service Criteria and in the Federal Motor Carrier Safety Regulations (FMCSR). This summary is based upon an Interim Report covering work whose specific objectives are to evaluate the technical adequacy of the OOS criteria for brake-adjustment and to make recommendations on revisions to either the OOS criteria, or the FMCSR to make them uniform, technically sound, practical (from an economic, safety, and enforcement perspective), and appropriate. Further work to be performed later in this study will be aimed at generating information that will aid motor carriers in knowing how often they need to adjust brakes. This first phase, however, emphasizes the OOS criteria per se.

This work is timely in the sense that approximately one million trucks were inspected in 1989 under the Motor Carrier Safety Assistance Program (MCSAP) using these OOS criteria and roughly 22 percent of the vehicles inspected were put OOS for brake system violations which were mostly due to brake-adjustment problems. (Overall, 41 percent of the vehicles inspected were put OOS.)

The study first included interviews with MCSAP inspectors in eight different states (Michigan, Wisconsin, New York, Maine, Oregon, Utah, California, and Georgia). These interviews showed that, although the inspectors had suggestions on various details of the brake inspection procedures and OOS criteria, they were satisfied for the most part with the OOS criteria for brake-adjustment. As a group, the inspectors were conservative with respect to changing the OOS criteria in that changes might cause confusion. Nevertheless, none of the inspectors thought that the criteria should be relaxed and, on the contrary, the adequacy of the "20 percent rule" for the number of defective brakes was questioned. Some inspectors believed that exceptions were needed, for example, for situations in which the push rod on one brake was backed-off and the brake rendered completely ineffective.

The study next involved a review and evaluation of recent studies on braking performance and the influence of brake-adjustment on the braking performance of heavy vehicles. In addition to pertinent references on the characteristics and components of air brake systems, the review emphasized data and results in reports from BMCS (now OMCS) and NHTSA; specifically reports entitled, "Brake Performance Levels of Trucks" and "The Effect of Brake-adjustment on Braking Performance." Based upon (a) the information derived from the review, and (b) the knowledge and experience of the researchers; two documents were written to provide an evaluation of data and procedures available for investigating brake-adjustment, OOS criteria, and braking performance. The nature of these documents can be surmised from their titles, namely, "An Assessment of Data Pertaining to the Influences of Out-of-Adjustment Level, Vehicle Configuration, Loading, and Brake Temperature on Braking Performance" and "Braking Performance—Relationships between Braking Efficiency, Vehicle Stability, and Brake Adjustment." Next, the researchers made preparations to perform analyses aimed at:

- Assessing the influences of brake-adjustment levels on stopping distance performance.
- Evaluating whether being able to stop within OOS limits from 20 mph is a good indicator of being able to stop safely from 60 mph.
- Identifying critical adjustment thresholds beyond which heavy vehicles cannot stop within a safe margin.
- Identifying key factors contributing to brake out-of-adjustment for manually adjusted brakes.
- Developing statistical measures pertaining to relationships between the key factors identified and stopping capability.
- Providing a sound quantitative basis for confirming or changing current OOS brake-adjustment criteria.

In order to obtain basic information for use in these analyses, several states were contacted to see if they had detailed brake inspection data that could be used to provide statistics on factors influencing stopping performance. Fortunately, although (a) only Oregon and Wisconsin were identified as having applicable data in electronic form suitable for statistical analysis by computer, and (b) the data saved by states are almost entirely on violations (as opposed to stroke data on brakes that were within adjustment limits or, for example, the qualities of inspected vehicles that were not in violation), it was discovered that NTSB (the National Transportation Safety Board) was gathering a sample of appropriate data on vehicles and brake-adjustment levels in the states of Florida, Pennsylvania, Illinois, Texas, and Oregon. The NTSB data, and also data from Oregon and Wisconsin, were installed into computer files and analyzed in connection with responding to the objectives of the last three bullet items listed above.

To respond to the first three bullet items above, calculations were made for predicting the influences of brake-adjustment levels on stopping distance. For these purposes, the phenomena associated with the "bottoming" of the push rod in the brake chamber were given special attention and new procedures for representing these phenomena were developed. These new procedures were incorporated into analysis techniques for predicting stopping distances similar to those techniques presented in the NHTSA work. This provided the means for making quantitative estimates of stopping performance for vehicles with various numbers of axles with various levels of brake adjustments and brake temperatures at different amounts of vehicle loading. For heavily laden trucks operating on roads with adequately high friction, the results of the analyses indicated the percentage increases in stopping capability due to adjustment levels, brake temperatures, and the number of axles on the vehicle.

Evaluations of the results of the analyses of stopping capability have produced the following findings:

- Brake-adjustment is most important in situations involving high temperatures, heavy loads, high pressures, and high friction at the tire/road interface. Results for stops from 60 mph at brake temperatures of 400°F and full load on a high friction road surface are appropriate for comparing the influences of brake-adjustment on stopping capability.

- Adjustment influences depend upon the pressure used in measuring stroke. Measuring stroke at 80 psi is less demanding (by 1/8 inch of stroke) than measuring stroke at 100 psi.

- Brake temperature has a strong influence on the torque capability of brakes that are out-of-adjustment (that is, beyond the readjustment point used as the limit in the OOS criteria).

- Much larger percentage changes in stopping distance occur at 60 mph compared to 20 mph.

- The influences of a backed-off brake are larger than "one brake demerit." Stopping distance discrepancies would be reduced if backed-off brakes were given demerits at least equal to 1.5 brakes in computing the "20 percent " criteria.

- The use of "brake-adjustment factors" based upon the stroke at each brake would provide a more uniform OOS criteria with respect to stopping capability. However, this would involve a more complex computation for the OOS criteria.

Analyses of the inspection data from Oregon, Wisconsin, and NTSB have identified the following factors associated with out-of-adjustment (OOA) brakes:

- The Oregon and Wisconsin files indicated that front axles are more likely to be OOA than rears, the rear axle in a tandem set is more likely, and trailer brakes are somewhat more likely than tractor brakes.
- Based upon the Oregon data, intrastate carriers of logs, sand, and ore are somewhat over-represented, and all private and interstate for-hire carriers are somewhat under-represented.
- The NTSB data indicate that automatic slack adjusters do well at reducing the number of brakes that are 1/4 inch beyond the readjustment point (one brake demerit by the OOS criteria); vehicles with retarders (engine brakes) have better levels of brake-adjustment; there is only a slight difference in brake-adjustment level between private and for-hire vehicles; in situations where the driver is responsible for brake-adjustment, the drivers appear to do as well as the maintenance people; tractors with model year before 1986 have much higher rates of defective (one brake demerit) brakes; the rear tandem drive axle is more likely to be OOA, and trailer axles are more likely to be OOA than tractor axles; and the differences associated with cargo body types, tractor cab styles, and trailer model year are not great.

The NTSB data have the detail necessary for estimating the stopping capabilities of all the vehicles inspected. The NTSB has also incorporated a calculation of braking efficiency with their data set. Analysis of their measure of stopping performance indicates that the current system of assigning brake demerits for computing the 20-percent criteria provides a reasonable separation between vehicles that are OOS and those that are not. Examination of the braking efficiency results indicates that calculations made for the vehicle in a fully-laden state (80,000 pounds) and at brake temperatures of 400°F provide a clear indication of the importance of brake-adjustment. In summary, both the mechanical analyses and the analysis of a sample of field measurements indicate that predictions of stopping capability can be used to provide a technically sound procedure for evaluating the uniformity of OOS criteria.

The results and findings developed in this first phase of the study support the following recommendations:

(1) Suggested changes in OOS criteria should be evaluated using the severity of the maintenance defect (in terms of how much braking capability is lost) and the influence of the change on the overall stopping capability distribution for a representative sample of vehicles such as those included in the NTSB data set.

(2) The matter of backed-off brakes should be given more attention in the OOS criteria. This is a much more serious maintenance defect than a brake whose stroke adjustment is 3/8 inch beyond the readjustment point. Perhaps a backed-off brake could be grounds for OOS by itself, or at least the backed-off brake should be counted as 1.5 brakes or 2.0 brakes in the 20 percent calculation.

(3) The following items should be considered in further examination of the OOS criteria:

- The pressure at which static stroke is measured;

- The use of a system for estimating the stopping capability of the vehicle and using that estimate for determining OOS;

- A penalty for having backed-off brakes (per Recommendation 2).

(4) The sections of the OOS criteria pertaining to front brakes need to be reworded so that it is explicitly clear as to when front brakes alone put vehicles OOS and how front brakes contribute to the 20-percent calculation when their defects are not severe enough to put the vehicle OOS based upon front brakes alone. If it is important to be able to put a vehicle out-of-service for both front brake violations and violation of the 20-percent rule, this should be explained also.

(5) With regard to the second phase of this study, it is recommended that the following items should be included:

- A new NTSB data set, gathered on non-interstate roads and currently being tabulated, should be added to the data files already assembled.

- The stopping capability calculation procedures developed in this study should be used to calculate the stopping capabilities of the vehicles included in the NTSB data sets.

- Stopping capability distributions for OOS and non-OOS vehicles should be made for the suggested modified forms of the OOS to provide a sound basis for evaluating the influences of these changes on the ability to separate vehicles based upon their stopping capabilities.

EVALUATION OF CRITERIA FOR
TRUCK AIR BRAKE ADJUSTMENT
INTERIM REPORT ON THE FIRST PHASE

1. INTRODUCTION

The focus of this evaluation is on the technical adequacy of the brake-adjustment criteria contained in the existing "Out-of-Service (OOS) Criteria" for brakes as stated in Appendix A, Part II of the North American Uniform-Driver-Vehicle Inspection Out-of-Service Criteria. [1] In 1989, these criteria were employed in the inspection of over one million trucks in the States that participated in the Motor Carrier Safety Assistance Program (MCSAP) with cooperation from the Commercial Vehicle Safety Alliance (CVSA). In these inspections, 41 percent of heavy trucks were put OOS and 54.6 percent of the inspected vehicles were put OOS because of brake problems. [2] The most frequent brake problem (estimated to be a large percentage of the brake problems) was brake-adjustment. Clearly, brake-adjustment is a major reason for placing heavy trucks OOS.

A reasonable reaction to the existing situation regarding brake-adjustment is that the current "system" or procedure for ensuring well maintained brakes does not work well enough. Perhaps the brake systems themselves cannot be adequately maintained given the pressures involved with being cost effective in the trucking business. In that case, new types of braking systems, perhaps ones with automatic slack adjusters, for example, might be in order for certain trucking applications. Another possibility might be that brake-adjustment has not been adequately accounted for in the maintenance schedules of trucking organizations. Furthermore, the ability to check stroke (brake-adjustment) is hindered because the push rods of brakes are not readily accessible for measurement. Although this lack of accessibility has always been the case, it may have become an even greater problem in recent years given changes in the design of trucks, the trucking business, and the expectations of the driver population. Again, there may be a need for a technological solution if current trucks are to operate with well adjusted brakes.

In the current environment in which many trucks are put OOS for brake-adjustment, the objectives of this project are pertinent and they are intended to contribute to an improved system for monitoring and maintaining the adjustment of truck brakes. The broad goals of this study are to (1) reevaluate the brake OOS criteria, and (2) generate information that will tell motor carriers how often they need to adjust brakes. Specifically, the objectives are as follows:

(1) Evaluate the technical adequacy of the existing "Out-of-Service (OOS) Criteria" for brakes. The focus of this evaluation will be on the brake-adjustment criteria.

(2) Make recommendations on revisions to either the OOS criteria or the Federal Motor Carrier Safety Regulations (FMCSR) to make them uniform, technically sound, practical, and appropriate.

(3) Develop guidelines on brake inspection and maintenance, especially on brake-adjustment for drivers, mechanics, and motor carriers.

(4) Determine what effect vehicle use has on brake-adjustment.

(5) Determine how often brakes require adjustment for various types of vehicles and various types of operations.

To meet these objectives, the project work has been organized into two phases. This Interim Report represents a summary of the findings and work performed in the first phase. The work reported here concentrates specifically on the first two objectives concerning OOS criteria, although general results pertaining to objectives 3, 4, and 5 have been derived from studying available databases containing information obtained during vehicle inspections.

The work in the remaining tasks of this study ("Phase II") will provide more information regarding how often brakes need adjustment and guidelines for brake inspection and maintenance.

This report has extensive appendices that are copies of reports submitted previously in the first phase of the study. The titles of these appendices are as follows:

- "Findings from Interviews of MCSAP Inspectors" (Appendix A)
- "Literature Review" (Appendix B)
- "Braking Performance—Relationships between Braking Efficiency, Vehicle Stability, and Brake Adjustment" (Appendix C)
- "An Assessment of Data Pertaining to the Influences of Out-of-Adjustment, Vehicle Configuration, Loading, and Brake Temperature on Braking Performance" (Appendix D)
- "Evaluation of Brake Adjustment Criteria, Analysis Report" (Appendix E)

The main body of this report consists of a sequence of sections covering the following topics:

- Description of the OOS criteria related to brake-adjustment;
- Interviews with MCSAP inspectors;
- Mechanical analyses for relating stopping capability to brake-adjustment levels;
- Statistical analyses associating operational and vehicle factors with brake-adjustment violations;
- Combined mechanical and statistical analysis for challenging the technical adequacy and uniformity of the OOS criteria;
- Summary of significant findings concerning the OOS brake-adjustment criteria; and
- Recommendations regarding the appropriateness of the OOS brake-adjustment criteria.

The following sections summarize and re-organize material given in the appendices, and in some cases, fill in pertinent technical details that are not presented elsewhere. The preceding Executive Summary provides a concise overview of the study including background on how the work was accomplished, results and findings of the analyses performed, and recommendations concerning changes in the OOS criteria, and further study of the OOS criteria.

2. SUMMARY OF THE OOS BRAKE ADJUSTMENT CRITERIA

This section provides a brief explanation of the OOS criteria for brake-adjustment for those who may not be familiar with the requirements of the North American Uniform Out-Of-Service Criteria. [1] Direct quotations from Reference [1] are presented as one of the items in the literature reviewed in Appendix B. The goal here is to explain the "20 percent rule," and the meanings of a "defective brake" and our term, "brake demerits."

According to the criteria, a vehicle is to be put OOS if the number of defective brakes is greater than or equal to 20 percent of the required number of brakes on the total vehicle being inspected. The total vehicle includes all of the units making up a combination vehicle consisting of trucks, tractors, trailers, dollies, etc. Essentially, one brake is required for each axle end, that is, two brakes are required for each axle, and the total number of brakes is equal to two times the number of axles on the total combination.

With regard to brake-adjustment, the number of defective brakes is determined by special rules. These rules first include the specification of readjustment limits for the different sizes of brake chambers used on air-braked heavy trucks. Next, the rules involve means for relating the level of brake-adjustment, as determined by the stroke of the push rod, to an equivalent number of defective brakes. (We have tended to call these numbers "brake demerits" in subsequent parts of this report.)

The rules for brake-adjustment place a given brake into one of three categories with respect to the number of defective brakes, namely, (1) not defective; (2) warranting a penalty equal to 1/2 of a defective brake; and (3) warranting a penalty equal to one defective brake. A brake is not categorized as defective if the stroke of the push rod is less than the readjustment limit (sometimes called the "readjustment point") for the size and type of brake chamber installed for that brake on the vehicle being inspected with the engine off and the reservoir pressure at 80 to 90 psi with the brakes fully-applied. A brake counts as one defective brake if the stroke (under the same conditions as above) is 1/4 inch or more beyond the readjustment limit. In addition, a brake whose stroke falls in the range from (and including) the readjustment point up to (but not including) 1/4 inch beyond the readjustment point is to count as 1/2 of a defective brake in the computation of the number of defective brakes.

It is our understanding from examining informal minutes of past CVSA meetings that the reasoning behind these selections of categories for the equivalent number of defective brakes has to do with estimating the influence of brake-adjustment on the stopping capability of the vehicle being inspected. The intention is that vehicles should be put OOS and not allowed to proceed if, due to brake-adjustment, the vehicle is sufficiently lacking in stopping capability to be considered adequately safe to continue to operate and carry cargo on the highway.

Given the above intention of the OOS criteria, we have adopted the term "brake demerits" to use in situations where we are discussing changes in the OOS brake-adjustment criteria to make them more uniform with respect to reflecting the level of stopping capability due to various levels and states of brake-adjustment. For example, we have considered the possibility of counting a fully backed-off brake as 1.5 or 2.0 brake demerits or "defective brakes" in the original terminology. The rationale for assigning this number of brake demerits is based on estimates of the percentage change in stopping distance due to a backed-off brake.

3. INTERVIEWS WITH MCSAP INSPECTORS

The study included interviews with MCSAP inspectors in eight different states (Michigan, Wisconsin, New York, Maine, Oregon, Utah, California, and Georgia). Appendix A contains a detailed report presenting the findings from the interviews and describing how the following seven questions were used in the interview process:

- How is brake-adjustment inspected?
- How do you record brake-adjustment in relation to the vehicle being inspected?
- What do you know about vehicles with brakes out-of-adjustment?
- What do you think might be done to improve highway safety through better brake-adjustment and brake inspection procedures?
- What are your views on the OOS criteria for brakes?
- How often do brakes need to be adjusted?
- Have we missed something of importance and relevance?

The interviews provided practical information and informed opinions regarding topics related to these seven questions. The practical and pragmatic information gathered during the interviews combined with the examination of the findings of pertinent previous studies (see Appendices B, C, and D) contributed to the development of an analysis plan that involved both mechanical and statistical analyses.

More specifically, the interviews with inspectors provided a better understanding and practical perspectives on brake-adjustment procedures and equipment. They have shown that the inspectors have a general understanding of the relationships between brake-adjustment levels, lining condition, drum condition, and pneumatic timing (and the influences of brake valves) on stopping performance. However, this is not a quantitative understanding; rather, the inspectors have a qualitative feel for the elements of a satisfactory braking system. Their training, study, and experience appear to have provided them with the knowledge needed to measure and judge the quality of air brake systems.

The following statements summarize results regarding OOS criteria and brake maintenance.

OOS Criteria for Brake-adjustment

With respect to OOS criteria, the interviews were aimed at identifying (a) problems with the current OOS criteria, (b) aspects of brake OOS criteria that require further research, and (c) recommended changes in brake OOS criteria. The trend of the inspectors was to suggest tightening the criteria. No inspector said that the criteria should be relaxed in some manner. Even so, the results of the interviews show that, although the inspectors did have numerous suggestions on a variety of aspects of the OOS criteria for brakes, they were for the most part satisfied with the OOS criteria as it applies to brake-adjustment.

Three inspectors favored tightening the criteria for situations in which obvious maintenance deficiencies were apparent even though 20 percent of the brakes were not defective. In particular, exceptions were suggested for situations in which one brake was rendered inoperable or completely backed-off. One inspector was aggravated by experiences in which vehicles were proceeding on with one defective brake because the owners knew that the vehicle would pass the 20 percent rule.

There was one suggestion that the 20 percent rule may not be adequate for stopping fully-laden heavy trucks from high speeds. Research on this subject was recommended. Also one inspector felt that consideration should be given to reinstating the old rule requiring that the stroke on the front brakes be within 1/2 inch of each other.

Nevertheless, the inspectors' comments indicated that, as a group, they were conservative with regard to changing the OOS criteria, in that changes might cause confusion.

Brake Maintenance

A number of the topics discussed in the interviews fall under the heading of "Brake Maintenance" related subjects. Specifically, the brake-maintenance related topics were as follows:

- Brake inspection procedures and equipment.
- Factors such as the number and distribution of axles, the number of brakes out-of-adjustment, and the degree of out-of-adjustment which place vehicles out of service.
- Types of vehicles and segments of the industry that may have a disproportionate number of vehicles placed OOS for brake-adjustment.

- Frequency for adjusting brakes for different vehicle configuration and operating conditions.
- The use and effectiveness of devices that warn drivers of imminent brake failures and defects, including out-of-adjustment.
- The use and effectiveness of devices that automatically adjust brakes.

Our general interpretations of the results for these topics are based on responses from most of the question areas used in the interviews. (See the responses to the specific questions listed in Appendix A for statements on detailed matters.) The following ideas have been derived from talking to brake inspectors:

1. Quantitative information is available on which brakes tend to be out-of-adjustment. For example, the information saved in computerized form in Wisconsin appears to be useful for studying out-of-adjustment differences from brake to brake on the vehicles inspected.
2. The inspectors observe that heavy vehicles in seasonal enterprises such as logging and construction tend to have brakes out-of-adjustment. Also, refuse haulers have been singled out. These results have not been quantified in many states, but perhaps some of them can be verified quantitatively using the data recorded in Oregon.
3. The inspectors' approaches to questions concerning frequencies of brake-adjustment indicate the importance that they place on company policy rather than on the type of service or the type of vehicle the company employs. A very important observation is that each company needs to establish its own brake-adjustment schedule for its operation. (We have noted this same approach being recommended by brake component suppliers to their customers.)

Perhaps the most important finding from the interviews will be that the key to aiding truckers in maintaining proper brake-adjustment is to establish procedures that each trucking company can use itself (or the trucking company can be strongly encouraged to use if they have a poor inspection record) to determine the appropriate brake inspection and brake maintenance schedules for their operations.

4. MECHANICAL ANALYSES FOR STOPPING CAPABILITIES

An Approach to the Study of Brake-adjustment Criteria

The approach used in this study involves a combination of mechanical principles, experimental findings, and data from field inspections and investigations. Some of the work is based primarily upon mechanical analyses, and some involves statistical treatment of data gathered during inspections. In this sense, the examination of brake-adjustment criteria employs a multidisciplinary approach in which (a) the mechanical aspects of brake system performance are used to relate stopping distance to patterns of brake-adjustment levels, and (b) statistical associations between "key factors" and brake-adjustment levels are used to infer relationships between those key factors and stopping capability. The goal of the analyses (both statistical and mechanical) is to provide a sound quantitative basis for confirming or changing current OOS brake-adjustment criteria.

Before proceeding to discussions of the analyses, the differences between the terms "key factors" and "patterns-of-adjustment level" will be distinguished and the relationships between these terms will be explained.

The term "key factors" pertains to matters like vehicle configuration (number of trailers and number of axles), type of trucking operation (seasonal, for-hire, heavily-laden vehicles, etc.), the use of rented units, the use of the trailer brake valve, company policies with regard to brake maintenance (training, procedures for determining readjustment cycles, and responsibilities in the organization), the use of special equipment (retarders, automatic slack adjusters, stroke indicators, etc.), severity of service (frequency of severe braking, downhill operation, or stop-and-go delivery), etc. In the context of this study, "key factors" mean any of the above matters (plus any other things) that can be determined to be associated with brakes being OOA (particularly at the OOS level) during MCSAP inspections.

The phrase "patterns-of-adjustment level" means the amount of static stroke at each brake (by unit, axle, and side). Mechanical analyses have been performed to relate various patterns of adjustment levels to predicted measures of braking performance. However, with regard to relating patterns of adjustment levels to key factors, the Oregon, Wisconsin, and NTSB databases have been explored to find associations indicated by the available data. The associations obtained by examining the inspection data do not contain the deterministic rigor of mechanical analyses, but rather rely on using statistical techniques to interpret the available data. Given the distinctions that we have made here, the patterns of adjustment level are useful for evaluating the technical adequacy of OOS criteria and the key factors will aid later on in the second phase of this study in connection with associating the characteristics of trucking operations with the likelihood that vehicles will have brakes that are out-of-adjustment.

A Phenomenological Method for Calculating Stopping Capability

The method presented here is an extension of the work of M. Flick in "The Effect of Brake Adjustment on Braking Performance." [3] Flick's study includes dynamometer testing of brakes, vehicle tests, and calculations of braking performance. The results of that study provided the fundamental information used here to account for the influences of static stroke and brake temperature. (Appendix D contains a review of Flick's work and a presentation of the type of data available for use in mechanical analyses.)

The primary difference between Flick's work and our work is that Flick developed an "empirical" model for making calculations of the influence of static stroke and temperature on stopping distance, and we developed a "phenomenological" procedure for assessing the influence of brake-adjustment on stopping capability. This phenomenological procedure uses a semi-empirical model in which the form of the model is based upon mechanical considerations and the "coefficients," or the "pertinent mechanical properties," are evaluated to match experimental data.

Many of the ideas presented later in this report are based on an understanding of the phenomena associated with the operation of brake chambers when brakes are out-of-adjustment. The following discussion uses a series of four questions in outlining basic features of the phenomena involved in determining the influence of brake-adjustment on stopping capability.

First, to provide an overview, consider the question: Where does the stroke go? The push rod in the brake chamber moves in response to pressure in the brake chamber. As indicated in Figure 1 (taken from Reference [4]), the brake shoes touch the drum at 5 or 10 psi corresponding typically to about 0.5 inches of stroke for a well-adjusted chamber. As the brake lining wears, the stroke at which the shoes touch the drum will increase, and if the brake is not readjusted soon enough, the brake-adjustment may become poor as indicated in the lower half of Figure 1.

Once the linings touch the drum, stroke increases by about an inch as the pressure increases to 100 psi. As shown in Figure 1, this would account for the stroke being 1.5 inches at cool brake temperatures. Due to drum expansion, more stroke is needed at higher

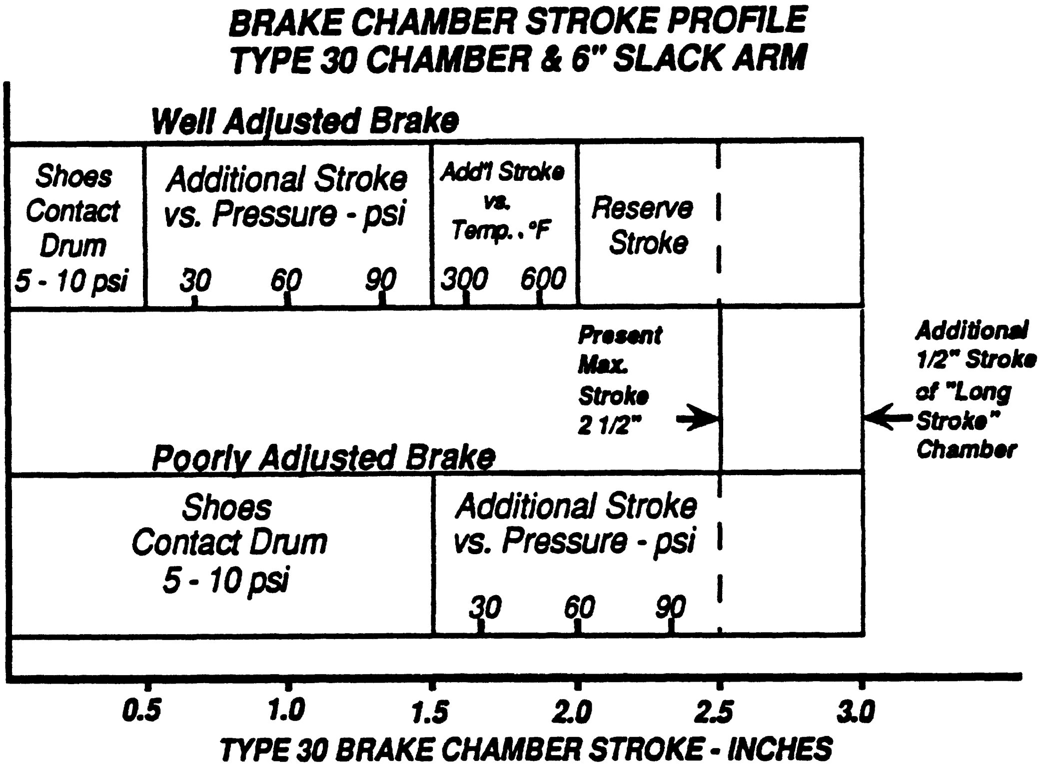


Figure 1. Stroke accounting

brake temperatures. Stroke may increase at about 0.1 inches per 100°F or at elevated temperatures. Even a well-adjusted brake may be at the readjustment point of 2 inches for the example given in Figure 1. For the poorly adjusted brake illustrated in Figure 1, the push rod would "bottom-out" in the brake chamber and there would be no reserve stroke left for temperature effects.

In summary, the phenomena described in this discussion include (a) the "pushout pressure" for the linings to touch the drum; (b) the compliance of the linings, shoes, etc. as the pressure increases the force actuating the brake; and (c) drum expansion due to temperature.

To develop ideas concerning these phenomena, consider a quantitative means for presenting an answer to the question: How does a brake chamber work in a brake? To aid in answering this question, Figure 2 illustrates (a) the characteristics of an air chamber showing the actuation force on the pushrod as a function of stroke and pressure, and (b) an "operating line" representing the relationship between actuating force and stroke due to compliances in the brake and its actuating mechanism. The mechanical advantage, due to the S-cam and the slack arm length, is included in this representation of the compliance. In the example shown in Figure 2, the brake has an initial "slack" of 2.0 inches at the pushout pressure. At 100 psi, the simultaneous solution, satisfying both the chamber characteristics and the relationship determined by the operating line, is an actuating force of about 1700 pounds which is approximately equivalent to the actuating force attainable at 60 psi if the initial slack had been around 0.75 inches of stroke instead of 2.0 inches. In other words, for the example given in Figure 2, there has been a reduction of approximately 60 percent in the actuating-force capability for the brake and this reduction is due to the amount of overall slack determining where the operating line starts.

Given the above quantitative information, the next question is: How are these phenomena represented? A mechanical model for representing the phenomena associated with the onset of bottoming of the push rod in the brake chamber and the compliances in the brake has been introduced into this study. As illustrated at the top of Figure 3, this model consists of 3 elements—(1) a pushrod with an actuating force equal to the chamber pressure, P_c, times the chamber area, A_c, and "return springs;" (2) a non-linear bottoming effect represented by a stroke at which this effect starts, S_c, and a non-linear stiffness that increases as stroke, S, increases beyond S_c, and (3) a so-called "lining" model which represents the operating line introduced in Figure 2, consisting of an overall slack, S_L, and a stiffness, K_L. Since S_L is changing with temperature during a stop, the model has two

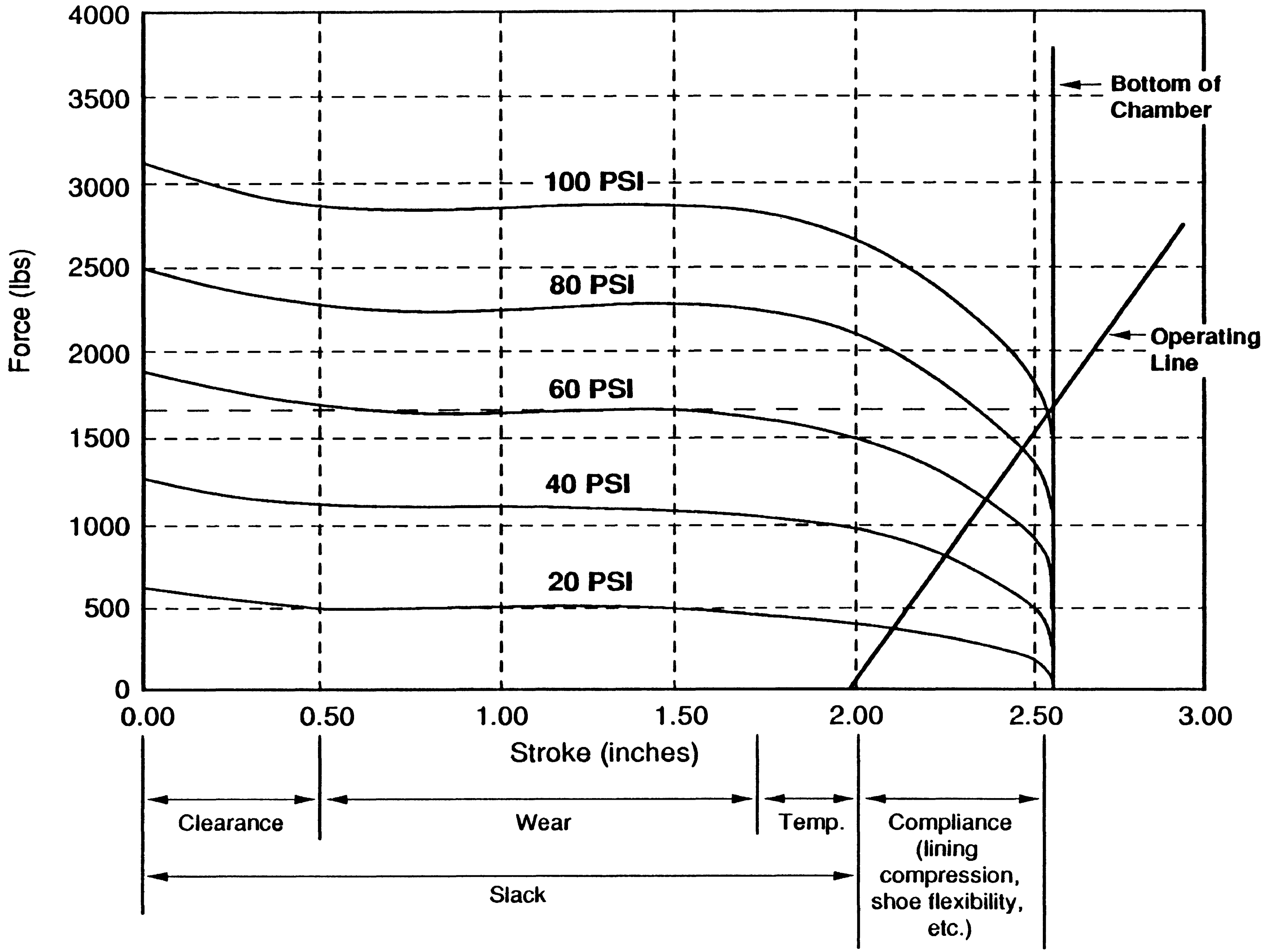


Figure 2. Operating line superimposed on brake chamber characteristics.

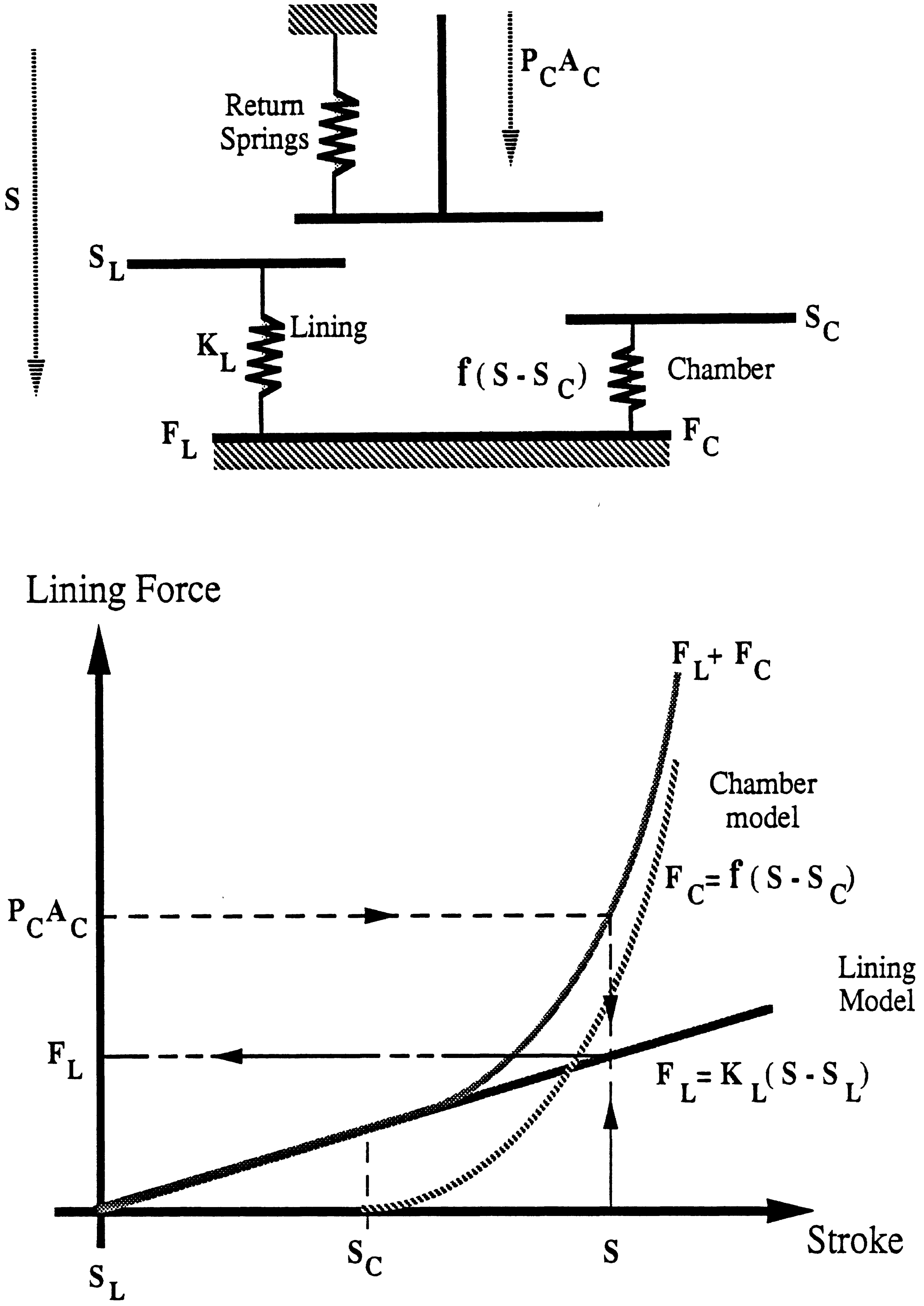


Figure 3. Mechanical model of the chamber in a brake.

inputs, specifically, the chamber pressure and the component of S_L that is changing as temperature changes. The stroke of the pushrod, in combination with the stiffnesses for the lining and the chamber (as indicated in Figure 3), produces two forces—F_c, which is the bottoming force on the chamber; and F_L, which is the actuating force on the lining. The output of the model is, of course, the actuating force on the lining.

Since the model contains non-linear elements and one of the parameters, S_L, is changing during a stop; the calculation of the actuating force, F_L, involves a special sequence. This sequence can be explained with reference to the graphs presented at the bottom of Figure 3. At a given instant, the stroke, S_L, can be computed from the temperature and the thermal properties of the drum. This means that the total force (F_c + F_L) is known as a function of the stroke S. Given the value of the actuating force P_cA_c on the pushrod, the total force function can be used to solve for S. (That is, $P_cA_c = F_c + F_L$.) Once S is determined the lining model can be used to calculate F_L, the actuating force that is effective in producing brake torque. This sequence is illustrated by the dashed lines and arrows included in Figure 3 for a situation in which $S > S_c > S_L$.

The final question to be considered here is: What is the whole braking system like? In that regard, the phenomenological model described above may be embedded into a procedure for calculating stopping distance. In order to do this, one needs to include computations of (a) the chamber pressure for each brake, (b) the brake torque due to the actuating force on the linings, (c) deceleration, velocity, and stopping distance of the vehicle, and (d) the temperature rise at each brake. Figure 4 illustrates how these separate computations fit together to represent a braking vehicle operating on a high friction surface such that no wheels are locking. In this case, stopping capability may be predicted for any pressure that is below the pressure that will cause a wheel to lock. In particular, this type of calculation procedure is useful for predicting the influences of various patterns of brake-adjustment levels on the ultimate stopping capability of a total vehicle whose weight, W, is at the maximum weight allowed for that vehicle.

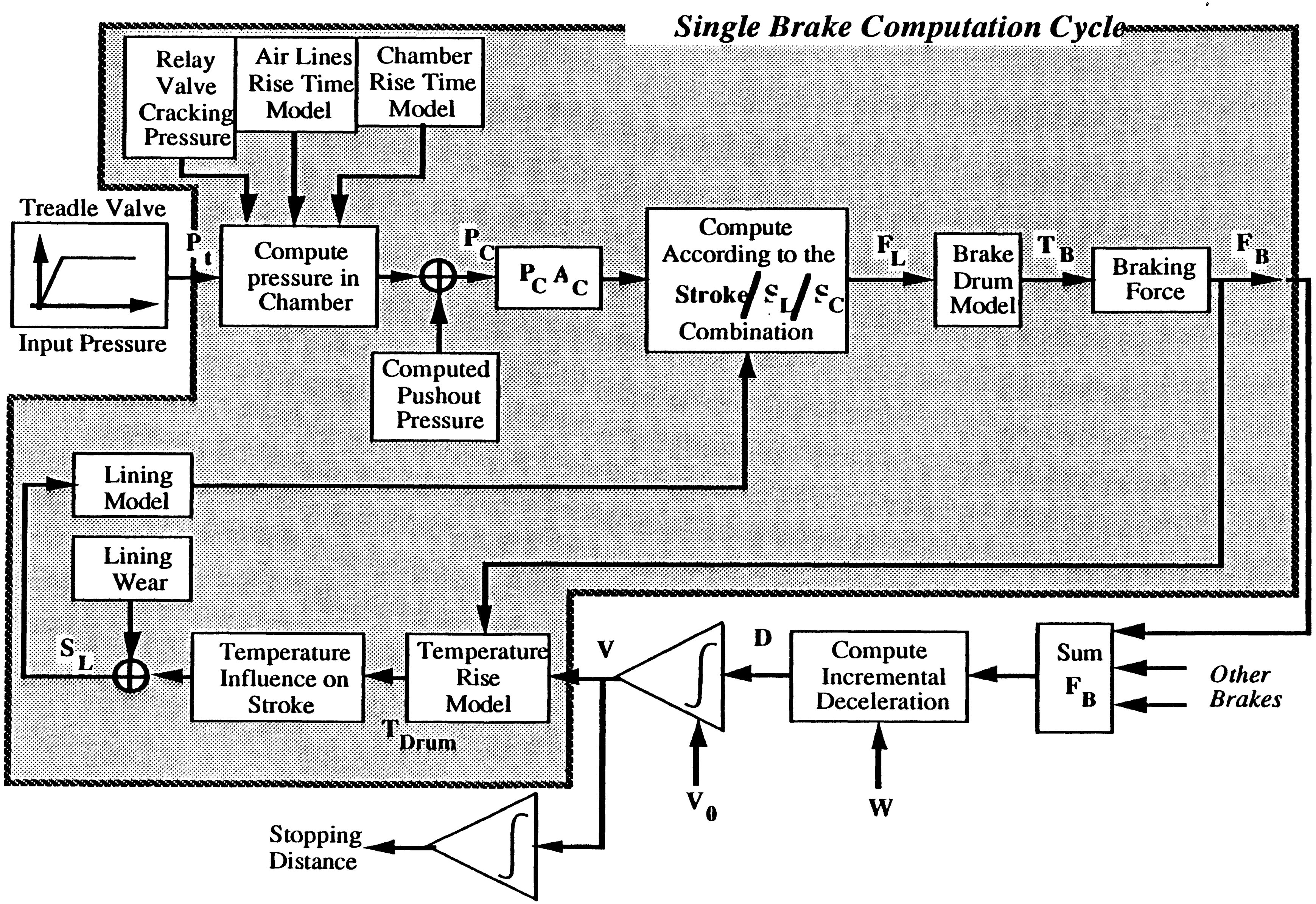


Figure 4. Calculation of stopping capability.

Results from Mechanical Analyses of Stopping Capability

(The results presented here are extracted and condensed versions of material presented in Appendix E, the Analysis Report.)

The mechanical analyses consisted of two types. The first type involved applying the phenomena-based calculation procedure to a number of "pathological" examples that previous studies ([3] in particular) had shown to challenge the ability of the OOS criteria to be uniformly demanding with respect to stopping distance. The second type of analysis involved the development of "brake-adjustment factors" that could be used to estimate relative changes in stopping capability due to the level of brake-adjustment for a given brake.

The analyses of the pathological cases produced predictions of brake torque capabilities and stopping distance performance from 60 mph and from 20 mph. Calculations were made for 3, 5, and 9 axle trucks (6, 10, and 18 brakes) at selected combinations of brake-adjustment levels as listed in Table 1.

For these cases, all brakes whose adjustment levels were not prescribed were taken to be fully-adjusted (FA). In addition, for the 3 and 5 axle trucks, a supplementary set of combinations was defined as Cases 3', 4', and 5'. For these cases, the brakes which were previously FA were set to be RA-1/8 (1/8 of an inch short of RA, the readjustment point). Each of the above measurements of stroke level represented the results of measurements made at static, cold conditions (70°F).

The pressure at which the static stroke is evaluated is an important factor in assessing the braking performance of a truck. In particular, measurements made at 80 psi are less demanding than those made at 100 psi, in the sense that a brake that reaches the readjustment point at 80 psi will be approximately 1/8 inch beyond the readjustment point at 100 psi. Hence, the pressure at which static stroke is measured needs to be considered in evaluating the results.

TABLE 1— Pathological Patterns of Brake-adjustment Levels

Case	Combination	Description
Case 1	FA	• All brakes are fully-adjusted
Case 2	All RA-1/8"	• All brakes stroke 1/8" before the readjustment point
Case 3	FA plus 20% RA+1/8"	• Some brakes are at half brake demerit level (enough to constitute 20% OOS). The strokes of those brakes are 1/8" beyond the readjustment point.
Case 4	FA plus 20% RA+3/8"	• Some brakes are at 1 brake demerit level (enough to constitute 20% OOS). The strokes of those brakes are 3/8" beyond the readjustment point.
Case 5	One Backed-off brake	• One brake is completely backed-off so that it does not generate any braking torque.

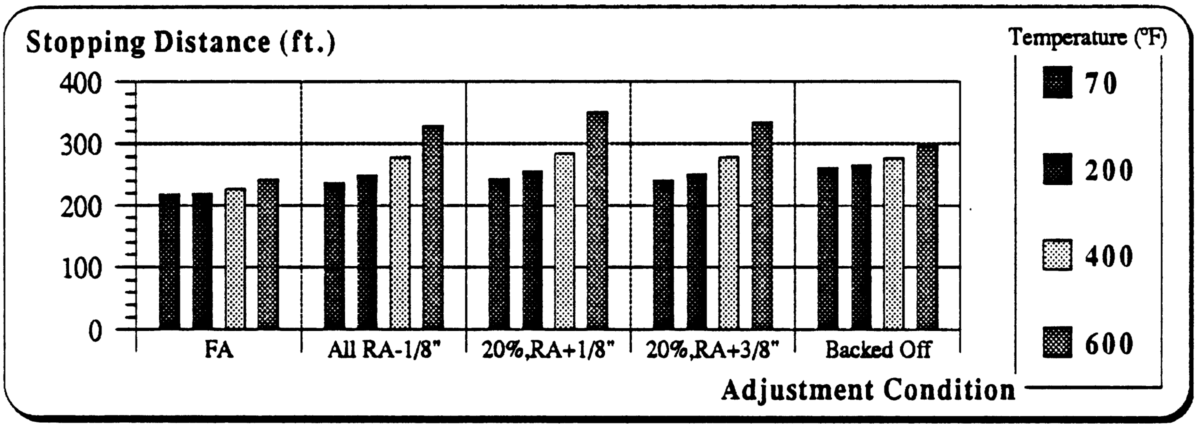
An example set of results for Cases 1 through 5 and 3', 4' and 5' are presented in Figures 5 and 6. (The complete set of results for 3, 5, and 9 axle vehicles is presented in Appendix E.) The results of the calculations show the influences of brake temperature and adjustment pattern on stopping distance and also the percentage increase in stopping distance. Given that many factors other than brake-adjustment may influence stopping distance itself, the results expressed by percentage changes in stopping distance are taken to be the most meaningful for assessing the influence of brake-adjustment on stopping capability.

The results (particularly those for "percent increase in stopping distance" displayed in Figures 5 and 6) support the following observations:

- Brake temperature has a remarkably large influence on the results obtained for cases in which brakes are out-of-adjustment beyond the readjustment point.

Stopping Distances (60mph) of a 3 Axle Truck With Various Adjustment Conditions (Measured at 80 psi) as a Function of Temperature

Adjustment Case / Temp.	Case1 FA	Case 2 All RA-1/8"	Case 3 20%,RA+1/8"	Case 4 20%,RA+3/8"	Case 5 Backed Off
70	217	237	244	241	262
200	219	249	256	251	266
400	227	278	285	279	277
600	242	328	351	334	297



Percent Increase in Stopping Distance as a Function of Temperature and Adjustment Conditions

Adjustment Case / Temp.	Case1 FA	Case 2 All RA-1/8"	Case 3 20%,RA+1/8"	Case 4 20%,RA+3/8"	Case 5 Backed Off
70	0	9	12	11	21
200	1	15	18	16	23
400	5	28	31	29	28
600	12	51	62	54	37

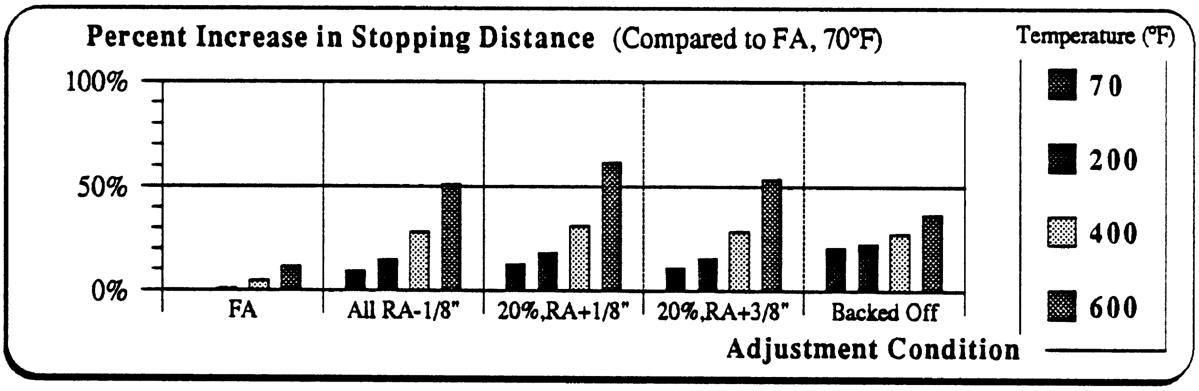
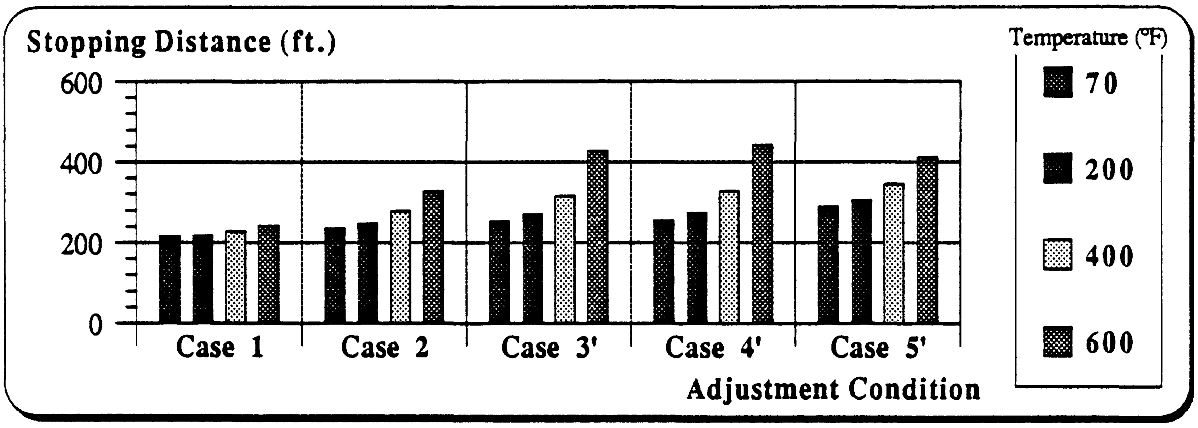


Figure 5. Influence of adjustment and temperature on the stopping distance of a 3 axle truck at 60 mph.

Stopping Distances (60mph) of a 3 Axle Truck With Various Adjustment Conditions (Measured at 80 psi) as a Function of Temperature

Adjustment Case Temp.	Case 1	Case 2	Case 3'	Case 4'	Case 5'
70	217	237	253	256	290
200	219	249	271	275	306
400	227	278	316	328	345
600	242	328	427	444	412



Percent Increase in Stopping Distance as a Function of Temperature and Adjustment Conditions

Adjustment Case Temp.	Case 2	Case 3'	Case 4'	Case 5'
70	9	17	18	34
200	15	25	27	41
400	28	46	51	59
600	51	97	105	90

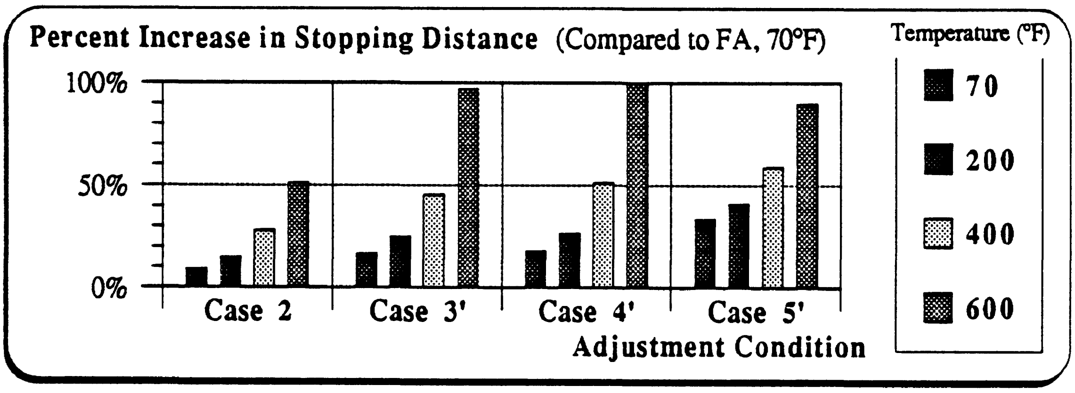


Figure 6. Influence of adjustment and temperature on the stopping distance of a 3 axle truck at 60 mph (modified adjustment cases).

- A situation in which all brakes are close to the readjustment point, but not over it, will cause nearly the same percentage increase in stopping distance as those for a vehicle that is in violation of the 20-percent criteria for brake-adjustment.
- At temperatures less than or equal to 400°F, one backed-off brake on a three-axle vehicle will cause approximately as much loss in stopping capability as that for vehicles that are in violation of the 20 percent criteria.
- Comparisons of the results for cases 3', 4', and 5' (that is, cases in which the brakes that are not in violation are close to the readjustment point) with those for cases 3, 4, and 5 indicate that the condition of the brakes that are not out-of-adjustment have a lot to do with the increase in stopping distance, especially at elevated temperatures.

These observations summarize the main observations obtained other than the relatively obvious observation that the influence of one backed-off brake reduces as the number of brakes (axles) on a vehicle increases. Also, the comparison of results obtained at 20 mph with those obtained at 60 mph indicates that the percentage changes in stopping distance at 60 mph are much larger than they are at 20 mph. (See Appendix E for more details.)

The first type of analysis described above consisted of straightforward predictions of brake torques and stopping capabilities. The second type of analysis was aimed at more difficult issues such as identifying "critical adjustment thresholds beyond which heavy vehicles cannot stop within a safe margin" (quoting the Statement of Work for this study). In a sense, the first type of analysis provided background ideas for this new aim. In order to pursue the meaning of this aim with regard to evaluating OOS criteria for brake-adjustment, ideas behind "brake-adjustment factors" will be discussed next.

Given the above description, the second type of analysis has a more abstract and philosophical tone than a straightforward analysis of stopping distance. The results summarized here are based on concepts and ideas related to selecting levels of stopping distance degradations and reductions in safety margins with respect to those stopping capabilities available to trucks with excellent maintenance making stops under very favorable operating conditions. The logic and rationale for this approach is that the current OOS criteria represent the combined judgment of many knowledgeable people thereby providing a reasonable starting point for considering the implications and meanings of changes in defining critical adjustment thresholds or patterns of adjustment thresholds from brake to brake on a vehicle.

In summary, the current OOS criteria provide an initial indication of the amount of loss in stopping capability and safety margin that is currently deemed acceptable by the CVSA/MCSAP community. Perhaps higher goals may be acceptable in the future, but the current indications from MCSAP inspections are that many trucks are having difficulty meeting the current goals for brake-adjustment, given the hardware and maintenance practices currently employed. The following results emphasize means by which stopping distance goals as derived from current criteria might be applied more uniformly across the spectrum of possible brake-adjustment situations.

The idea here is to assign brake-adjustment factors to various ranges of brake-adjustment. These factors are to be used to estimate changes in stopping capability for any given pattern of brake-adjustment levels. In this context, vehicles might be put OOS if the estimated increase in stopping distance was 20 percent for example. In this way, brake demerits would be associated with the influences of adjustment level on the brake's torque capability, and vehicles would be put OOS based upon their loss in stopping capability due to brake-adjustment factors.

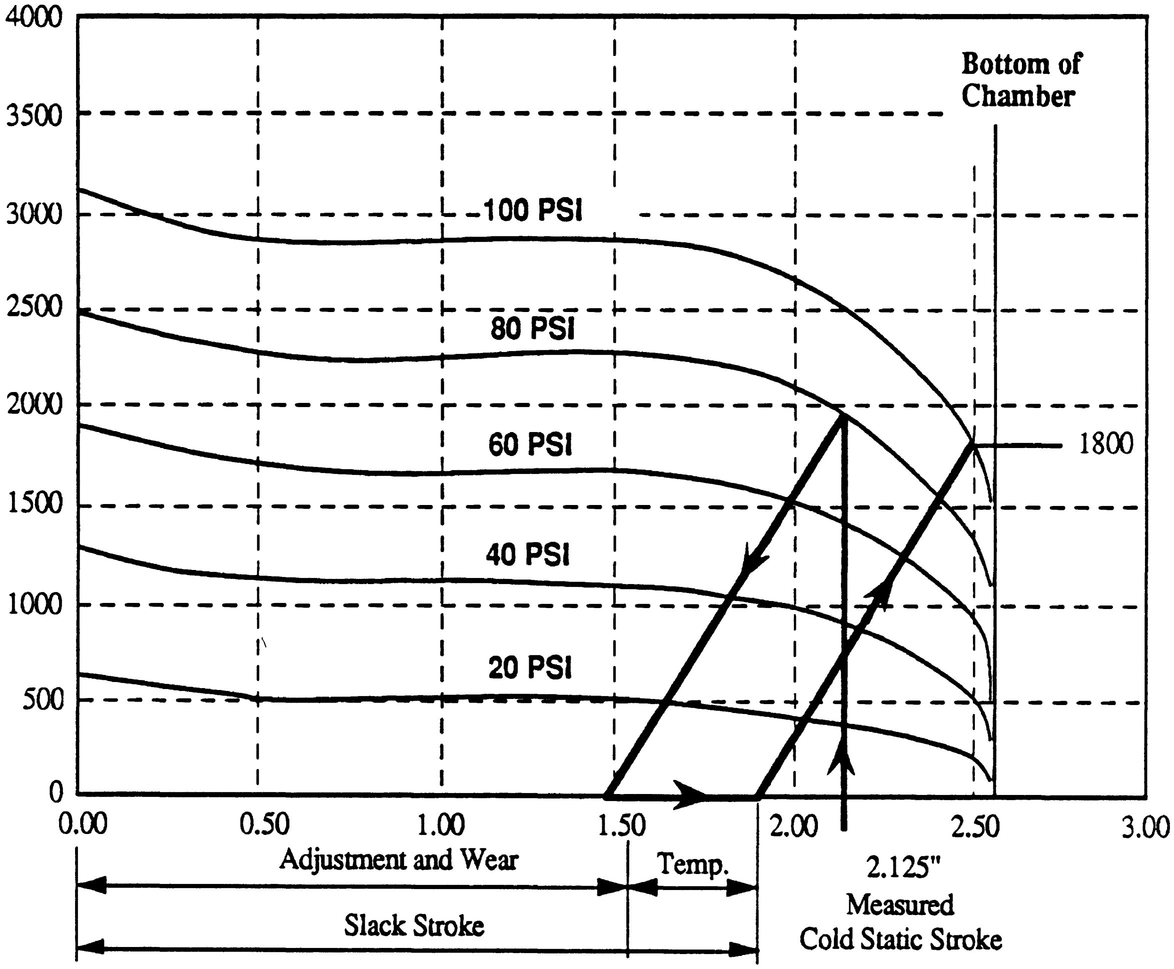
The method for determining the desired brake-adjustment factors is based upon examining brake chamber characteristics. For example, consider a brake whose cold static stroke is measured to be 2.125 inches at 80 psi (a situation that would be represented as 0.5 defective brakes in the current 20 percent rule). As indicated by the lines with arrows in Figure 7, the adjustment factor for this brake would be determined by the following sequence of considerations:

(1) The "slack stroke" is determined by proceeding down an operating line from 80 psi, where the static stroke was measured, to the horizontal axis. (This is the total clearance stroke that would be measured using a pry bar, for instance, to move the pushrod when the brake is cold.)

(2) The slack stroke is increased by an amount corresponding to a temperature factor and other factors due to self actuation, etc. (In this case, a brake temperature of 400°F plus 0.1 inch of in-stop stroke increase were used.)

(3) The actuating force capability is determined by proceeding up an operating line until it intersects the 100 psi characteristic for the brake chamber. (This is

1/2 Brake Demerit



$$\frac{F}{F_{ref}} = \frac{1800}{2850} = 0.632$$ ➡

Net Result: 63% of the fully adjusted braking force for a cold static stroke of 2.125 inches measured at 80 psi

Figure 7. Determination of a brake adjustment factor.

the pushrod force that would be available for actuating the brake in a full brake application at 400°F.)

This actuating force may be expressed as a fraction of the available force by dividing it by the actuating force for a fully-adjusted brake. In this case, the result is a brake-adjustment factor of 0.63.

Table 2 provides the results of carrying out this process for pertinent ranges of stroke measurements. The ranges have been chosen to provide means for accounting for the situations covered by the pathological cases studied earlier. Specifically, for example, brakes close to the readjustment point have an adjustment factor equal to 0.77, and fully backed-off brakes have a factor equal to zero, while the factors for the 0.5 defective brake range and the 1.0 defective brake range are 0.63 and 0.30 respectively.

Table 2. Brake-adjustment Factors at 400°F

Range of stroke(s) with respect to the readjustment point RA	Brake-adjustment factor representing the stroke range
"fully-adjusted" stroke(s)	1.0
$RA - 1/8 \leq s < RA$	0.77
$RA \leq s < RA + 1/4$	0.63
$RA + 1/4 < s < RA + 1/2^*$	0.30
$RA + 1/2^* \leq s$ *use for type 30 chambers and bottom -1/8 for other types	0.0

There is a caveat that needs to be considered when applying these brake-adjustment factors. The factors are keyed to what a fully-adjusted brake will do. If different brakes have different torque capabilities in the fully-adjusted state, these differences need to be taken into account. A common situation is that front brakes have approximately 50 percent of the torque capability of rear brakes. Also, when slack arm lengths and/or chamber areas differ from tractor rear brakes to trailer brakes, then the "AL" factors (chamber area times slack arm length) need to be included in the procedure for estimating changes in stopping distance due to brake-adjustment. The following example, presented in Table 3, illustrates the computation for a situation in which a 3-axle (6-brake) truck has all brakes fully-adjusted except one rear brake which is at a cold stroke of RA +1/8 and another is at RA + 3/8.

Table 3 Example Calculation of the Change in Stopping Capability

brake #	adjustment level	adjust. factor	relative AL etc.	relative torque
1	FA	1.0	0.5	0.5
2	FA	1.0	0.5	0.5
3	FA	1.0	1.0	1.0
4	FA	1.0	1.0	1.0
5	RA+1/8	0.63	1.0	0.63
6	RA+3/8	0.30	1.0	0.30
		totals	5.0	3.93

To first approximation, the stopping distance is inversely proportional to the braking force. This means that in the above example (Table 3), the change in stopping distance due to brake-adjustment is approximately given by 5.0/3.93 which equals 1.27. In other words, the estimated stopping distance is 27 percent longer with the arrangement of brake-adjustment levels given in Table 3 than it would be if all brakes were fully-adjusted.

Results from this brake factor approach are in agreement with results from calculations using the more complete and detailed calculation procedure; as well they should be, since the brake-adjustment factors are derived from an approach which is very nearly the graphical equivalent of the phenomena-based calculations. (Nevertheless, this approximate approach should be regarded cautiously at low speeds even though it can be adopted with confidence at high speeds like 60 mph. See Appendix E for more detail.)

Furthermore, as indicated in Appendix E, the above procedure can be applied to a wide range of brake-adjustment situations to provide a measure of the associated change in stopping distance capability. The concept portrayed there is as follows: if the OOS criteria were related to a target-limit for the level of allowable reduction in stopping capability as determined by the use of brake-adjustment factors, a more uniform consideration of the importance of various patterns of OOA would be obtained.

5. STATISTICAL ANALYSES FOR ASSOCIATIONS WITH BRAKE-ADJUSTMENT LEVELS

Available Data from Brake Inspections

(The following material is extracted primarily from Appendix E, particularly Sections 3 and 4.)

Databases developed by the states of Oregon and Wisconsin were obtained and analyzed to address the relationships between adjustment levels and key factors. In addition, in mid-November of 1990, a very complete database (for our purposes in this study) was obtained from the National Transportation Research Board (NTSB) for a sample of nearly 1000 trucks. The NTSB data provides information that can be used to compare the stopping capability of vehicles that are OOS with those of vehicles that are not OOS (see Section 6), thereby providing a means for assessing the ability for OOS criteria to separate vehicles based on the stopping capabilities of those vehicles.

Oregon Data. A magnetic tape with 20,233 records containing coded inspection data was obtained from the state of Oregon. These data covered all CVSA inspections in 1989. The format of the Oregon data was better suited to a structured, or hierarchical, file. In this application, the file structure includes two different types of records. At the first level, there is one record for each vehicle inspected. These records include trucks with no violations, trucks with brake violations, and trucks with other violations. The records at Level 1 describe the carriers' operating authority and the configuration of the truck. The configuration is described in a series of fields for up to six units (tractor, semitrailer, etc.). Each unit is characterized in terms of the unit type, CVSA decal, make, state of registration, and whether it was placed out of service. The unit type codes are the following:

Power Unit		Trailer	
BU	Bus	ST	Semitrailer
TT	Tractor	FT	Full trailer
TR	Truck	PT	Pole trailer
		OT	Other trailer
		DC	Dolly converter

The second level of records describes individual brake violations. Each record identifies the unit having the violation, the type of unit, and whether the violation put the unit OOS. The available brake violation codes include the following:

Brake Violation Codes

B20	Defective brakes exceed 20%
BBA	Brake-adjustment
BPR	Push rod (on steering axle)
BSA	Slack adjuster (on steering axle)
BSB	No steering axle brakes

The BP20 code (defective brakes exceed 20%) seems redundant since subsequent BBA (brake-adjustment) codes follow for each of the brakes individually. A number of other codes describe brake violations not related to adjustment.

The configuration of the vehicle can be determined from the combination of units identified. For each configuration, the violation codes listed above can be located by unit number. No actual pushrod travel measurements are recorded, and violations cannot be located with regard to axle or axle-end.

General results from the 1989 Oregon inspection data are as follows. Of the 20,233 vehicles inspected, 22.1 percent had no violations, 45.7 percent had brake violations, and the remaining 32.1 percent had other violations. Overall, 34.4 percent of the trucks inspected were put OOS, and brake violations were responsible for about 80 percent of the vehicles put OOS. Focusing on the 45.7 percent (9,250 vehicles) that had one or more brake violations, 59.6 percent of these were put OOS. There were a total of 29,021 brake violations on the 9,250 vehicles having one or more brake violations. In other words, trucks with brake violations in Oregon have an average of about three brake violations per vehicle.

Wisconsin Data. A magnetic tape containing coded information on all brake violations in 1989 was provided by the state of Wisconsin. Wisconsin inspects both *intra*state and *inter*state trucks and a code is available to distinguish the two. Coding is also available to identify the location of each brake violation in terms of the unit number, the axle number, and axle end (left or right). In addition, the following three-character codes identify the nature of the brake violation.

	Violation Codes
BP1	Pushrod travel exceeds 1.75 inches
BP2	Pushrod travel exceeds 2 inches
BPN	No pushrod movement when brake applied
BPA	Pushrod travel is improper
BPU	Difference in pushrod travel (L/R) exceeds 0.5 inch

Each unit of the vehicle is described separately, and is identified as unit "one of two" (1/2), or "two of two" (2/2). Unit type is coded as truck, tractor, semitrailer, or full trailer. Axles are numbered within each unit, and axle ends are identified as left or right. Thus, the available information is adequate to determine the distribution of violations by unit of the vehicle, and by axle location on each unit.

The Wisconsin data has information on 4,156 trucks, each with one or more brake violations, for a total of 8,725 violations. The average number of brake violations per truck having one or more brake violations is 2.1 in Wisconsin, as compared to 3.1 from the Oregon data.

NTSB Data. During the course of the inspector interviews, a National Transportation Safety Board team was encountered in Oregon conducting a series of random brake-adjustment inspections. The value of the data being collected by NTSB to this study was immediately apparent from the data form which is included as Figure 8. The specific advantage provided by the NTSB data is stroke measurements for each brake on the vehicle regardless of whether the brake is in violation or not. Thus, the NTSB data can be processed to provide distributions of adjustment levels for brakes that are not in violation, as well as those that are in violation.

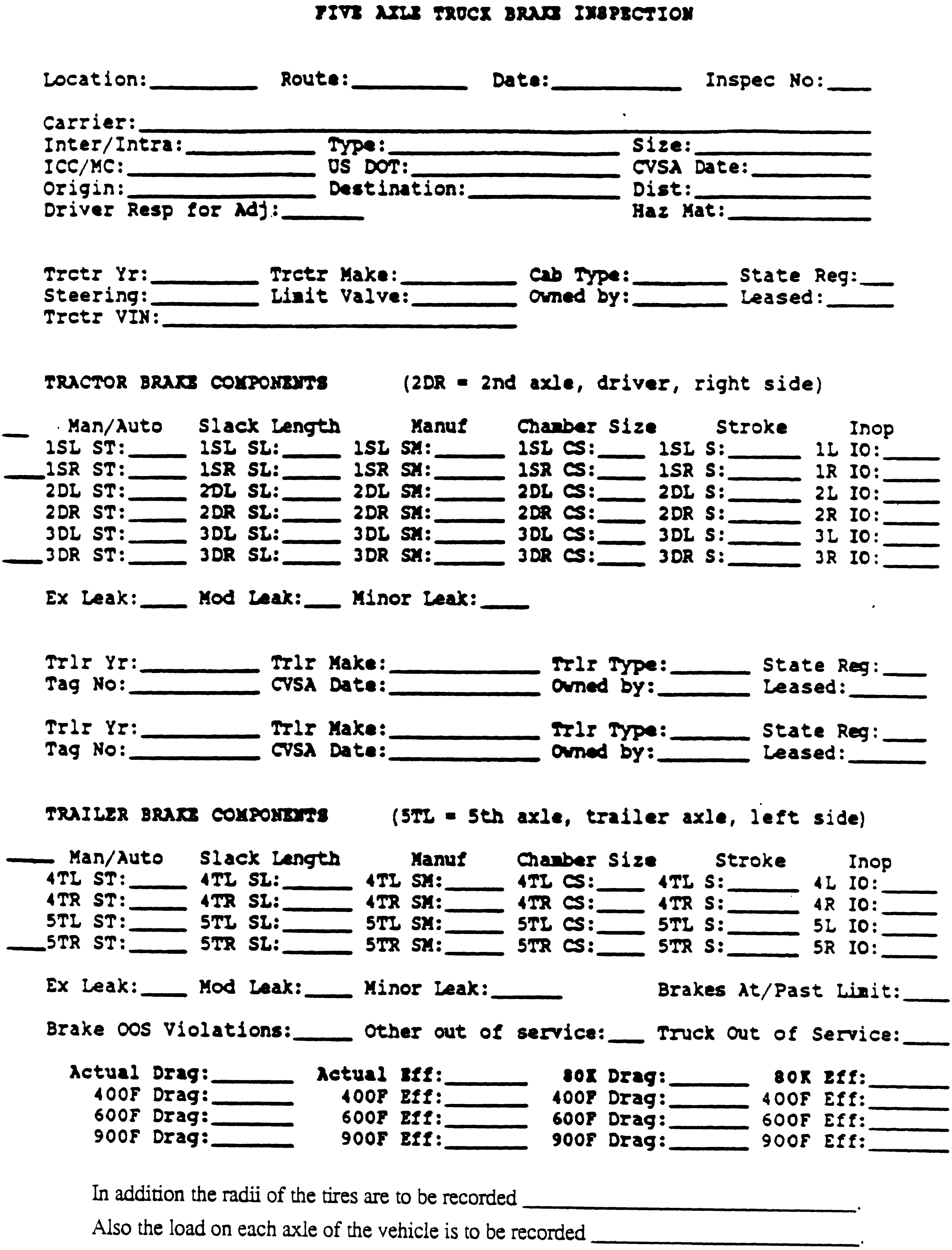
The NTSB data have other advantages. The manufacturer and chamber sizes are recorded and manual brakes are distinguished from automatic slack adjusters. Since the surveys were all conducted at weigh stations, the actual loaded weight on each axle was recorded and has been combined with the data on the attached form.

NTSB conducted these inspections over two or more days in each of five states (Florida, Illinois, Pennsylvania, Texas, and Oregon). Approximately 180 five-axle trucks were inspected in each state for a survey total of over 900 vehicles. In each case, the trucks were selected at random by taking every nth truck with n selected so that the inspection team could keep up. (The inspections were rapid because there was one inspector for each axle plus coordinating and data-recording personnel.)

Summary of Results from the Statistical Analyses of the Inspection Data

With regard to identifying key factors contributing to brake OOA for manually adjusted brakes, the results are summarized as follows:

•(1) Our review and analysis of existing data on brake-adjustment violations has produced little information related to the maintenance practices of the



FIVE AXLE TRUCK BRAKE INSPECTION

Location: ____ Route: ____ Date: ____ Inspec No: ____

Carrier: ____
Inter/Intra: ____ Type: ____ Size: ____
ICC/MC: ____ US DOT: ____ CVSA Date: ____
Origin: ____ Destination: ____ Dist: ____
Driver Resp for Adj: ____ Haz Mat: ____

Trctr Yr: ____ Trctr Make: ____ Cab Type: ____ State Reg: ____
Steering: ____ Limit Valve: ____ Owned by: ____ Leased: ____
Trctr VIN: ____

TRACTOR BRAKE COMPONENTS (2DR = 2nd axle, driver, right side)

	Man/Auto	Slack Length	Manuf	Chamber Size	Stroke	Inop
____	1SL ST: ____	1SL SL: ____	1SL SM: ____	1SL CS: ____	1SL S: ____	1L IO: ____
____	1SR ST: ____	1SR SL: ____	1SR SM: ____	1SR CS: ____	1SR S: ____	1R IO: ____
	2DL ST: ____	2DL SL: ____	2DL SM: ____	2DL CS: ____	2DL S: ____	2L IO: ____
	2DR ST: ____	2DR SL: ____	2DR SM: ____	2DR CS: ____	2DR S: ____	2R IO: ____
	3DL ST: ____	3DL SL: ____	3DL SM: ____	3DL CS: ____	3DL S: ____	3L IO: ____
____	3DR ST: ____	3DR SL: ____	3DR SM: ____	3DR CS: ____	3DR S: ____	3R IO: ____

Ex Leak: ____ Mod Leak: ____ Minor Leak: ____

Trlr Yr: ____ Trlr Make: ____ Trlr Type: ____ State Reg: ____
Tag No: ____ CVSA Date: ____ Owned by: ____ Leased: ____

Trlr Yr: ____ Trlr Make: ____ Trlr Type: ____ State Reg: ____
Tag No: ____ CVSA Date: ____ Owned by: ____ Leased: ____

TRAILER BRAKE COMPONENTS (5TL = 5th axle, trailer axle, left side)

	Man/Auto	Slack Length	Manuf	Chamber Size	Stroke	Inop
____	4TL ST: ____	4TL SL: ____	4TL SM: ____	4TL CS: ____	4TL S: ____	4L IO: ____
	4TR ST: ____	4TR SL: ____	4TR SM: ____	4TR CS: ____	4TR S: ____	4R IO: ____
	5TL ST: ____	5TL SL: ____	5TL SM: ____	5TL CS: ____	5TL S: ____	5L IO: ____
____	5TR ST: ____	5TR SL: ____	5TR SM: ____	5TR CS: ____	5TR S: ____	5R IO: ____

Ex Leak: ____ Mod Leak: ____ Minor Leak: ____ Brakes At/Past Limit: ____

Brake OOS Violations: ____ Other out of service: ____ Truck Out of Service: ____

Actual Drag: ____	Actual Eff: ____	80% Drag: ____	80% Eff: ____
400F Drag: ____	400F Eff: ____	400F Drag: ____	400F Eff: ____
600F Drag: ____	600F Eff: ____	600F Drag: ____	600F Eff: ____
900F Drag: ____	900F Eff: ____	900F Drag: ____	900F Eff: ____

In addition the radii of the tires are to be recorded ____.

Also the load on each axle of the vehicle is to be recorded ____.

Figure 8. NTSB form.

owner/operator. However, three patterns of brake violation were observed that may be a consequence of some of the key factors originally identified in the Statement of Work. They are:

1. The front axle on tractors is more likely to be out-of-adjustment, and when there is a brake violation on the front axle of a tractor, most of the time both brakes on the axle are in violation. This finding is consistent with a continuation of the practice of backing-off the front axle brakes.
2. Semi-trailers are somewhat more likely to have brake violations than tractors. However, this finding was not as strong as expected and was not consistent in the Oregon and Wisconsin files.
3. The rear axle of tandem pairs was more frequently in violation in comparison to the front axle of the pair. This trend was evident on both tractors and semi-trailers.

•(2) Compared with the overall rate for brake-adjustment violations for the vehicles inspected in Oregon, intrastate carriers of logs, sand, or ores (one of the categories in their database) are 14 percent overinvolved in brake-adjustment violations. Intrastate carriers of general freight are 10 percent overinvolved. On the other side of the picture, intrastate private, interstate for hire, and interstate private are all underinvolved in brake-adjustment violations.

•(3) The Wisconsin database indicated that, for interstate hauls, tractor brake violations were 55 percent of the total; while semitrailer violations represented only 35 percent of the total. On the other hand, for intrastate hauls, tractors represented 31 percent and semitrailers represented 48 percent of the total. With regard to the location of brake violations, it was found that if one brake on an axle was OOA, the other brake on the axle was also likely to be OOA. For example, trailers had both brakes on an axle OOA in 47 percent of the cases; 21 percent of the left side brakes; and 26 percent of the right side brakes were OOA alone. In general, there were slightly more violations for the right side brakes than for the left side brakes for tractors and semitrailers.

With regard to developing statistical measures pertaining to the relationships between key factors and stopping capability, the results derived from NTSB data are summarized as follows:

•(1) Given that brake-adjustment can be related to stopping capability, it suffices to develop relationships between key factors and OOA levels. The NTSB data set provides information that can be used to develop statistical associations between levels of OOA and the factors entered into the NTSB database. The factors studied in these analyses include automatic versus manual slack adjusters, engine brakes (retarders) versus no retarder, carrier type, tractor model year, trailer model year, axle number and location, cargo body type, and tractor make and cab style. (See Table 4.)

•(2) The findings in the areas listed above are as follows:

- Automatic slack adjusters do very well at reducing the number of brakes that are more than 1/4 inch beyond the readjustment point (one defective brake by the OOS criteria).
- Vehicles with engine brakes tend to have better levels of brake-adjustment than vehicles without retarders.
- There is only a slight difference between private and for-hire vehicles with regard to brake-adjustment levels in the NTSB database.
- In situations where the driver is responsible for brake-adjustment, the drivers appear to do as well as the maintenance people in maintaining brake-adjustment.
- Tractors with a model year before 1986 have much higher rates of defective brakes per the brake-adjustment criteria.
- For trailers, there was no particular trend to the proportion of OOA brakes by model year.
- The results for axle location were that the rear tandem drive axle is more likely to be OOA and that trailer axles are more likely to be OOA than tractor axles.

Table 4. (continued on the next page)

Statistical Measures of the Association Between Key Factors and Stopping Capability

Data Source--NTSB Brake Inspections

Findings on the Proportion of Brakes Out-of Adjustment

Brake Adjustment by Axle Number and Location

	left		right	
axle	ooa	defect	ooa	defect
1	10.30%	9.95%	10.87%	9.61%
2	9.84%	7.44%	8.81%	10.18%
3	12.36%	9.73%	11.67%	10.41%
4	13.50%	13.73%	15.68%	12.36%
5	13.62%	13.50%	14.30%	14.87%
total	11.92%	10.87%	12.27%	11.49%

Out of Adjustment Status by Slack Type, Singles Only

	ok	ooa	defect	unk	total
auto	85.76%	10.61%	3.63%	0.00%	100.00%
manual	73.45%	12.80%	13.69%	0.06%	100.00%
total	76.41%	12.27%	11.27%	0.05%	100.00%

Brake Adjustment Status by Carrier Type

	ok	ooa	defect	unk	total
For-hire	76.03%	11.73%	10.74%	1.51%	100.00%
private	73.66%	12.63%	12.42%	1.29%	100.00%
unk	57.27%	25.45%	17.27%	0.00%	100.00%
total	75.29%	12.09%	11.18%	1.44%	100.00%

Brake Adjustment Status by Driver Responsibility for Adjustment

	ok	ooa	defect	unk	total
yes	75.65%	11.31%	11.54%	1.50%	100.00%
no	73.64%	13.47%	11.33%	1.56%	100.00%
unk	80.17%	12.17%	7.33%	0.33%	100.00%
total	75.29%	12.09%	11.18%	1.44%	100.00%

Table 4. (continued from the previous page)

Brake Adjustment Status by Tractor Model Year

year	ok	ooa	defect	unk	total
>1983	61.18%	10.02%	17.51%	11.29%	100.00%
1983	79.44%	8.89%	11.67%	0.00%	100.00%
1984	73.10%	12.62%	14.05%	0.24%	100.00%
1985	75.00%	11.85%	12.04%	1.11%	100.00%
1986	83.61%	8.61%	7.78%	0.00%	100.00%
1987	81.42%	11.11%	7.47%	0.00%	100.00%
1988	82.10%	14.81%	3.09%	0.00%	100.00%
1989	85.68%	8.72%	5.59%	0.00%	100.00%
1990	84.42%	8.72%	6.85%	0.00%	100.00%
1991	63.33%	13.33%	23.33%	0.00%	100.00%
unk	85.00%	11.67%	3.33%	0.00%	100.00%
total	77.63%	10.64%	9.55%	2.17%	100.00%

Brake Adjustment Status by Trailer Model Year

	ok	ooa	defect	unk	total
<1983	66.04%	14.71%	18.18%	1.07%	100.00%
1983	78.13%	10.63%	11.25%	0.00%	100.00%
1984	72.50%	12.86%	14.64%	0.00%	100.00%
1985	67.86%	18.21%	13.93%	0.00%	100.00%
1986	78.26%	11.59%	10.14%	0.00%	100.00%
1987	72.00%	12.33%	15.67%	0.00%	100.00%
1988	73.95%	14.47%	11.58%	0.00%	100.00%
1989	70.52%	16.98%	12.50%	0.00%	100.00%
1990	69.59%	15.54%	14.86%	0.00%	100.00%
unk	76.40%	13.20%	9.60%	0.80%	100.00%
total	71.77%	14.27%	13.62%	0.34%	100.00%

Brake Adjustment Status by Cargo Body Type

	ok	ooa	defect	unk	total
flatbed	74.67%	10.62%	14.71%	0.00%	100.00%
van	71.40%	15.63%	12.61%	0.36%	100.00%
tank	67.58%	12.50%	18.36%	1.56%	100.00%
dump	70.14%	13.19%	16.67%	0.00%	100.00%
other	73.21%	12.95%	13.84%	0.00%	100.00%
unk	75.00%	25.00%	0.00%	0.00%	100.00%
total	71.77%	14.27%	13.62%	0.34%	100.00%

- The differences found between different cargo body types are not great, but the tank vehicles had the lowest percentage of brakes that were properly adjusted.
- The differences between cab-over and conventional cab styles was not great, though the conventionals had a greater percentage of properly adjusted brakes than the cab-overs did.

Detailed results indicating the percentages of (a) properly adjusted brakes (ok), (b) out-of-adjustment brakes at the 0.5 defect level (ooa), (c) brakes out-of-adjustment at the 1.0 defect level (defect), and (d) unknown adjustment level (unk) are presented in Table 4 which covers the key factors discussed in the previous paragraph.

6. COMBINED MECHANICAL AND STATISTICAL ANALYSES FOR EVALUATING OOS CRITERIA

The purpose of these analyses is to challenge the ability of OOS criteria to separate vehicles according to their stopping capabilities. The vehicle and brake information contained in the upper portions of the NTSB data forms have the information needed to make estimates of the "braking efficiency" of the vehicle (see the last few lines of the data form shown in Figure 8). These calculations of braking efficiency were made by NTSB using a procedure explained by R. Heusser in SAE Paper No. 910126 entitled, "Heavy Truck Deceleration Rates as a Function of Brake adjustment." [5]

(In the future, we plan to make calculations using our phenomena-based procedures, however, that will require using the NTSB data to compute the stopping capability for each vehicle in the NTSB data set. We recommend doing this work in the second phase of this study.)

The braking efficiency technique used by NTSB produces results that, based upon the physics involved, should correlate well with the percentage changes in stopping capability and the use of brake-adjustment factors developed in this study. Hence, we believe that the NTSB braking efficiency can be used as a surrogate for stopping capability for the purpose of challenging the OOS criteria now.

Only the NTSB data have the potential to provide an objective evaluation of the brake-adjustment out-of-service criterion. This is the only source of information that includes actual slack measurements on all brakes - those that were not in violation as well as those that were. No state was found that tabulated information on brakes that were *not* in violation. In addition, the NTSB data include the chamber size which is essential for relating the slack measurement to the OOA criteria.

The detail in the NTSB data is sufficient to support calculations of approximate measures of stopping performance. One such measure is the braking efficiency computed by NTSB. Of course, calculation of the braking efficiency of each truck inspected is probably too complicated to be part of a MCSAP vehicle inspection procedure. However, simple modifications and/or extensions of the existing criteria could be evaluated using the NTSB data. The effect of different criteria on the distributions of braking efficiency for OOS trucks and non-OOS trucks could be calculated from the actual slack measurements and the vehicle and brake information in the NTSB file.

The following figures (Figures 9 and 10) show the separation and overlap between OOS and non-OOS vehicles obtained for the vehicles inspected by NTSB. The first set of results (Figure 9) is labelled 80K loading and 400°F to indicate that the braking efficiencies are calculated for the vehicle if it were loaded to 80,000 lbs. and the initial brake temperatures were 400°F. In contrast, the results in Figure 10 are for the actual loading of the vehicle and at the "default" temperature which means normal ambient temperature.

(The charts presented in Appendix E examine the distribution of calculated braking efficiencies for different loadings and brake temperatures for vehicles put out of service for brake-adjustment violations and those that were not put out of service for brake-adjustment violations. Calculated brake efficiencies are from the NTSB data. They were determined for the actual loading of the vehicle and for the vehicle if it were loaded to 80,000 pounds. There are two sets of four charts, one set for the actual loading of the vehicle, and one for the vehicle if loaded to 80,000 pounds. Within each set, the four charts represent the baseline case with no temperature-related expansion and then with the brakes at 400,600, and 900°F. (Only five-axle tractor-trailer units are included in the comparison.)

The OOS criteria used in making Figures 9 and 10 correspond to the current criteria. Specifically, OOS is restricted just to vehicles put OOS due to brake-adjustment problems. The rules relating to brake-adjustment as outlined in the North American Uniform Vehicle Out-of-Service Criteria Policy Statement were applied to the vehicles in the NTSB data. Brakes were classified as defective if they were inoperative or if the stroke exceeded the maximum readjustment length by 0.25 inches or more. Brakes were classified as OOA if the stroke exceeded the readjustment length by less that 0.25 inches, and two OOA brakes count as one defective brake. If the total of defective brakes on a combination was 20% or more of the brakes, the vehicle was classified as OOS. A defective brake on the steering axle also put a vehicle out of service.

Figure 9 shows how well the brake-adjustment OOS criteria discriminate between braking efficiencies. This chart for the 80K loadings is the fairest comparison, since it compares braking efficiencies given the same gross weight for the vehicles being compared. In this 400°F case, the OOS criteria do a good job of separating the two populations. There is some overlap in the tails, but the means of the two populations are clearly separated.

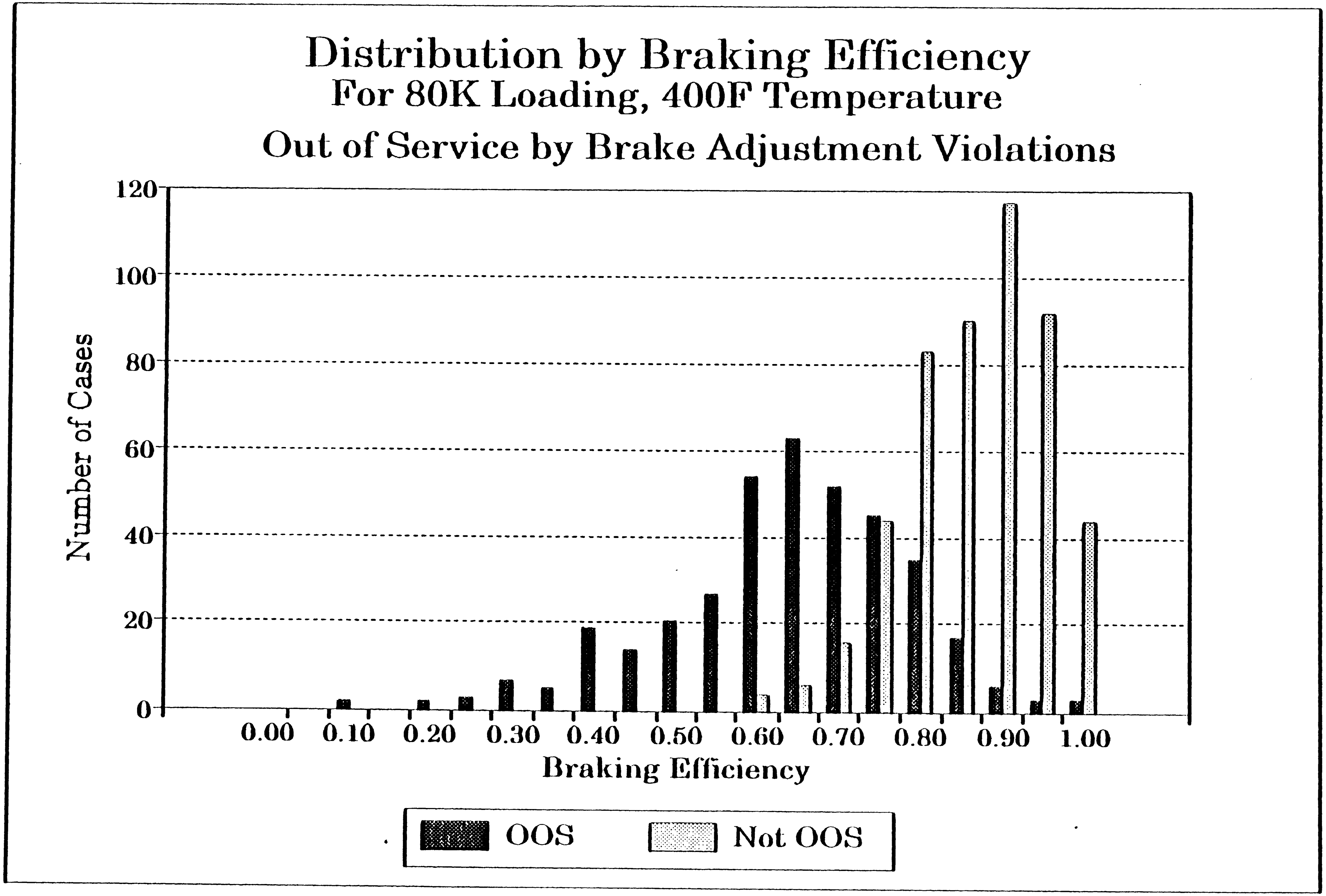


Figure 9. Distributions for OOS and non-OOS at 80k and 400 °F.

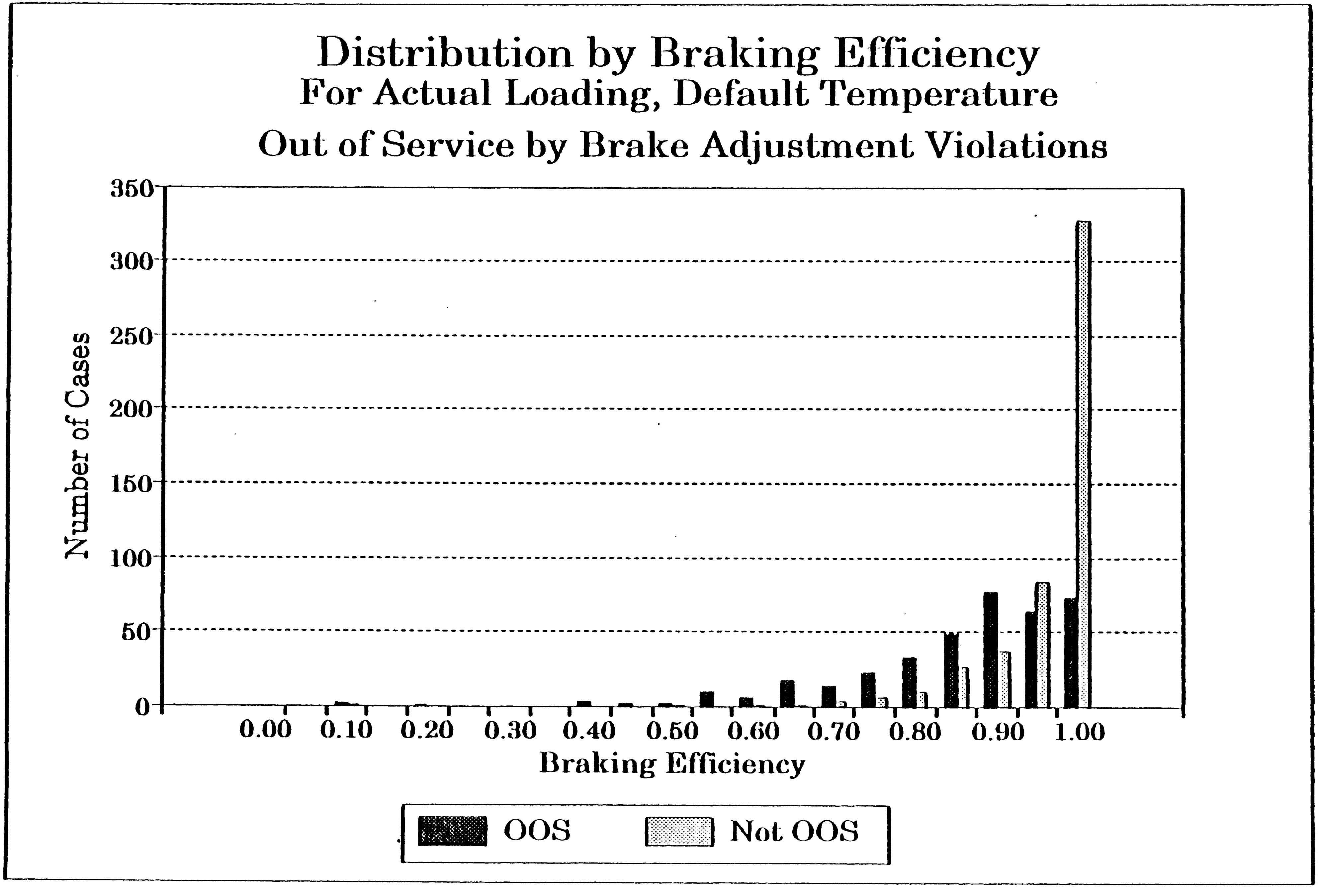


Figure 10. Distributions for OOS and non-OOS at actual loading and temperature.

The results for the actual loading are also of interest. These efficiencies were calculated for the gross weight of the vehicle at the time of the inspection and so show braking efficiencies for the two populations as they actually operate. For the default case, there is considerable overlap. Also, there are many cases that were put OOS, yet whose braking efficiencies are 1.00. (Note: Braking efficiencies as high as 1.0 are common in the NTSB definition because aft-to-fore load transfer is not included in the NTSB calculation. The NTSB calculation of braking efficiency assumes that the maximum braking force that a brake can produce is equal to 1/2 of the static axle load times a frictional value of 0.58.) In many of these cases, the braking efficiency would have been degraded if the vehicle were loaded to 80K, even though the NTSB braking efficiency was at 1.00 as the vehicle was actually loaded.

Providing a sound quantitative basis for confirming or changing the OOS criteria is a primary goal of this project. The results obtained, using the NTSB data, show that the current system of assigning brake demerits for computing the "20 percent" criteria provides a reasonable separation (in terms of NTSB's calculations for braking efficiency or braking drag) between vehicles that are OOS and those that are not.

In order to evaluate other OOS criteria suggested by this study, we propose that further calculations be made. These calculations would employ the stopping distance factors derived in this study (and described in Section 4 of this report) in connection with the inspection database containing the NTSB data. Frequency distributions (histograms) comparing OOS vehicles under each proposed criteria would be constructed. This would provide the basis for judgments concerning the ability of various proposed OOS criteria to separate vehicles according to their stopping capabilities.

7. SUMMARY OF FINDINGS CONCERNING OOS BRAKE-ADJUSTMENT CRITERIA

The following findings concerning the current OOS brake-adjustment criteria are based upon the results of the analyses and work performed in the first phase of this study:

—On the influences of brake-adjustment levels on stopping distance

•(1) The measurement of cold static stroke at 80 psi is much less demanding than measuring cold static stroke at 100 psi. This means, for example, that a stroke that is just at the readjustment point when 80 psi is applied will be approximately 1/8 inch beyond the readjustment point when 100 psi is applied. The reason for this can be seen by examining the "operating line" due to compliances in the brake superimposed upon the set of chamber characteristics for the brake involved. As the pressure is increased from 80 to 100 psi, additional stroke is consumed due to compression of the linings and compliances in the brake actuation system. When MCSAP decided to check stroke at 80 to 90 psi rather than at 100 psi, they could have reduced the readjustment points (1/2 brake demerit level) by approximately 1/8 of an inch if they wanted to be as stringent as the 100 psi stroke measurement would require. On the other hand, MCSAP may have desired to make the brake-adjustment criteria less demanding as well as respond to the concern that 100 psi applications may damage the brake system. Either choice seems possible depending upon the sentiments of the decision makers concerning the implications of brake-adjustment with respect to the "service worthiness" of the vehicles permitted to operate on the highway and not be put OOS.

•(2) The influences of a fully backed-off brake are considerably larger than those of a brake that is 1/8 inch beyond the one brake demerit level. This is particularly true for changes in stopping distance happening at low temperature levels (70°F and 200°F). This appears to be a situation which could be considered as one warranting a change in the OOS criteria.

Perhaps, if the OOS criteria were to be changed, the inspector would be expected to apply more than one brake demerit to a brake stroke that was close to the backed-off level of stroke. The results given in this study provide the information that could form the foundation for a recommendation with regard to the level of brake demerit to use for brakes that are fully backed-off and this level of demerit would be applied to brakes that are close to being fully backed-off. (As indicated in the next item, temperature influences will lower the braking capability of brakes that are close to being backed-off tending to cause them to approach backed-off brakes.)

•(3) The results, in general, show a significant influence of temperature on the predicted change in stopping distance at various levels of brake-adjustment beyond the readjustment point. Given that temperature has such a large effect on the predicted change in stopping distance, there is an issue concerning the level of temperature to use in comparing and evaluating stopping capabilities. Although one could devise a means for using all of the temperature results to obtain a composite measure of the percentage change in stopping performance, the results at 400°F and 80,000 lbs. appear to be representative and satisfactory for use in comparing the influences of brake-adjustment on stopping capability

—On whether being able to stop within the OOS limits at 20 mph is a reliable indicator of being able to stop safely at 60 mph within OOS limits.

•(1) The results indicate that percentage changes in stopping distances due to poor brake-adjustment are much larger at 60 mph than at 20 mph. There are two reasons for this. First, the influence of brake timing is much more important at 20 mph than it is at 60 mph. Even though the brake timing in the examples studied meet FMVSS 121 requirements, the maximum available torque is not applied for very long in the 20 mph stop, thereby decreasing the influence of brake-adjustment compared to that during a 60 mph stop. The second reason involves the temperature rise during a stop. This is a very small effect at 20 mph, but it is important at 60 mph for out-of-adjustment brakes that are close to bottoming out. The basic finding from the calculations is that the increase in drum expansion due to temperature rise has an important influence on braking capability for hot, poorly-adjusted brakes.

—On critical adjustment thresholds beyond which heavy vehicles cannot stop within a safe margin

•(1) The raw material presented in Section 1 of Appendix E show that stopping distance versus brake-adjustment results are highly dependent upon temperature conditions and the pressure level at which static stroke is measured as well as the level of adjustment. Although one could consider some composite measure of performance based upon a wide range of initial brake temperatures, vehicle loading conditions and road-surface conditions, the analytical work that went into developing the calculations indicates that the influences of brake-adjustment are most important with respect to stopping distance capability in situations involving high temperatures, heavy loads, and high friction at the tire/road interface. The finding here is that it is reasonable to evaluate the influences of brake-adjustment criteria at chosen sets of operating conditions. Examination of the overall results suggests that calculated stopping distances from 60 mph for vehicles laden to the maximum allowable limit are appropriate for examining the influences of various brake-adjustment criteria.

•(2) Section 4 and Appendix E (Section 3.3.2) presents a method for adding "backed-off" brakes into a brake "demerit" system like the one used in the current 20 percent OOS criteria. The idea is to augment the current 1/2 brake and 1 brake penalties used in computing the 20 percent factor employed in the OOS criteria. If these levels of brake penalties are viewed as "demerits," a completely misadjusted or backed-off brake could be assigned a demerit value to be used in computing a 20 percent factor that would be based upon the percentage reduction in stopping distance caused by various levels of misadjustment.

The net conclusion reached is that stopping distance discrepancies due to backed-off brakes could be reduced if backed-off brakes were given a penalty equivalent to at least 1.5 brake demerits. The criteria for calling a brake "backed-off" or "completely misadjusted" would be that the cold static stroke is greater than or equal to 2.5 inches for a type 30 chamber. For other types of chambers, an equivalent boundary could be set at the stroke required to reach the bottom of the chamber minus 1/8 of an inch.

•(3) The ideas presented in this study extend the notion of using brake-adjustment factors like those introduced for backed-off or completely misadjusted brakes. In this case, a scheme is presented for using estimated changes in stopping distance to determine OOS. The methodology involves assigning "brake force adjustment factors" to various ranges of brake-adjustment (see Table 2). The results indicate that it would be feasible to estimate changes in stopping capability using this approach, although it would require knowledge of "AL" factors (chamber size and slack arm length). Also, the lower torque capabilities of front brakes would also need to be factored into the calculation of stopping capability. Nevertheless, this method would improve the relationship of available stopping capability to OOS criteria for brake-adjustment.

•(4) There is already considerable sentiment for simplifying the OOS criteria. The above suggested methods for changing the OOS criteria may not appear to be simple, but they are not very complicated. Nevertheless, an issue to be decided is whether it is worthwhile to increase the complexity of the OOS criteria in order to reflect a more uniform relationship to stopping capability.

8. RECOMMENDATIONS REGARDING THE APPROPRIATENESS OF THE OOS BRAKE-ADJUSTMENT CRITERIA

The results and findings developed in this first phase of the study support the following recommendations:

(1) Suggested changes in OOS criteria should be evaluated using the severity of the maintenance defect (in terms of how much braking capability is lost) and the influence of the change in criteria on the overall stopping capability distribution for a representative sample of vehicles such as those included in the NTSB data set. By these standards, the current OOS criteria do a reasonably good job of separating vehicles by stopping capability.

(2) The matter of backed-off brakes should be given more attention in the OOS criteria. This is a much more serious maintenance defect than a brake whose stroke adjustment is 3/8 inch beyond the readjustment point. Perhaps a backed-off brake could be grounds for OOS by itself, or at least the backed-off brake should be counted as 1.5 brakes or 2.0 brakes in the 20 percent calculation.

(3) The following items should be considered in further examination of the OOS criteria for brake-adjustment: (The following items could be considered at CVSA/MCSAP meetings.)

- The pressure at which static stroke is measured.
- The use of a system for estimating the stopping capability of the vehicle and using that estimate for determining OOS. (In particular, the use of the brake-adjustment factors described in this report.)
- A penalty for having backed-off brakes (per Recommendation 2).

(4) The sections of the OOS criteria pertaining to front brakes need to be reworded so that it is explicitly clear as to when front brakes alone put vehicles OOS and how front brakes contribute to the 20 percent calculation when their defects are not severe enough to put the vehicle OOS based upon front brakes alone. If it is important to be able to put a vehicle OOS for both front brake violations and violation of the 20 percent rule, this should be explained also.

With regard to the second phase of this study, it is recommended that the following items should be included to further challenge the appropriateness of the OOS criteria:

(1) A new NTSB data set, gathered on non-interstate roads and currently being entered into computer format, should be added to the data files already assembled for this study.

(2) The stopping capability calculation procedures developed in this study should be used to calculate the stopping capabilities of the vehicles included in the NTSB data sets.

(3) Stopping capability distributions for OOS and non-OOS vehicles should be made for the suggested modified forms of the OOS to provide a sound basis for evaluating the influences of these changes on the ability to separate vehicles based upon their stopping capabilities.

9. REFERENCES

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