

Statistical And Mechanical Analyses Of Brake Adjustment Criteria For Heavy Trucks

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ABSTRACT

This paper presents mechanical and statistical analyses of the brake adjustment criteria in the North American Uniform Driver-Vehicle Inspection Criteria for heavy trucks. The statistical results of inspection data are derived from detailed NTSB roadside inspections of vehicles with S-cam brakes. The data indicated that 936 out of 2,146 vehicles inspected failed the OOS brake adjustment criteria. Of the 936 vehicles that failed the 20-percent rule because of brake adjustment, 480 had a computed braking capability greater than 80 percent of the braking capability that would be available if the vehicle had all of its brakes fully adjusted. The 480 vehicles could therefore be considered "false positives." None of the vehicles that passed the brake adjustment criteria had a computed braking capability less than 80 percent of the braking capability for the fully-adjusted condition. This paper presents two alternative methods to evaluate brake adjustment levels on heavy vehicles to reduce the false positives currently associated with the use of the 20-percent rule on brake adjustment.

BACKGROUND

This paper is based on a study entitled "Evaluation of Brake Adjustment Criteria for Heavy Trucks" conducted by the University of Michigan Transportation Research Institute (UMTRI) for the Federal Highway Administration (FHWA) Office of Motor Carriers.[1] Brake adjustment criteria for heavy trucks are specified in the North American Uniform Driver-Vehicle Inspection Criteria.[2] In 1989 these criteria were used in the inspection of more than 1 million trucks in States participating in the Motor Carrier Safety Assistance Program (MCSAP). In these inspections, 41 percent of the heavy vehicles were placed out-of-service. Of the out-of-service vehicles, 54.6 percent were placed out-of-service for brake system defects. The most frequently cited brake problem was brake adjustment [3].

An overriding concern regarding the brake adjustment problems with heavy trucks is that the current "system" or procedure for ensuring well-maintained brakes is not adequate. Perhaps the brake systems themselves cannot be

adequately maintained given the pressures involved with being cost effective in the trucking industry. Another possibility might be that brake adjustment has not been adequately accounted for in the motor carriers' maintenance schedules. Furthermore, the ability to check brake adjustment is hindered because pushrods are not always readily accessible for measurement. Although the lack of accessibility has always hampered efforts to keep brakes properly adjusted, it may have become an even greater problem in recent years given changes in the design of trucks, the trucking industry, and the demands on the driver.

This study addresses the criteria used to place heavy trucks out-of-service for out-of-adjustment brakes. A mechanical analysis of the brake system is used to develop alternative methods of evaluating in-service brake adjustment. Data from NTSB truck inspections are used for a statistical analysis of the effectiveness of the various brake adjustment criteria that are compared.

SUMMARY OF THE OOS BRAKE ADJUSTMENT CRITERIA

The North American Uniform Driver-Vehicle Inspection Criteria [2] includes a "20-percent rule" for brake defects. The rule covers certain mechanical defects (e.g., loose, broken or missing components, air leaks, etc.) and brake adjustment. Under the 20-percent rule a vehicle is placed out-of-service if "the number of defective brakes is equal to or greater than 20 percent of the brakes on the vehicle or combination." In the case of a combination vehicle, the brakes on all of the units in the combination (truck-tractor, semitrailer, converter dollies, etc.) are used in the application of the rule. Generally two brakes are required for each axle (one brake at each axle end) of the vehicle or combination. A five-axle tractor-semitrailer combination would have a total of ten brakes; two defective brakes would place the combination out-of-service.

The brake adjustment criteria classify each brake on the vehicle or combination into one of three categories with respect to the number of defective brakes:

- (1) not defective

- (2) 1/2 of a defective brake (at the readjustment limit or less than 1/4 inch beyond the readjustment limit), and
- (3) one defective brake (1/4 inch or more beyond the readjustment limit).

For the purposes of this paper, the discussion of the 20-percent rule relates to brake adjustment only. Considering only the brake adjustment criteria, either of the following are considered as one defective brake:

- (1) One brake at 1/4 inch or more beyond the readjustment limit.
- (2) Any two brakes at the readjustment limit or less than 1/4 inch beyond the readjustment limit.

A table of readjustment limits for different types and sizes of brake chambers is provided in the inspection criteria. The readjustment limits are 80 percent of the maximum stroke for the chambers listed. The inspection procedure includes instructions to bring reservoir pressure to between 90 and 100 psi, turn the engine off and then fully apply the brakes when measuring brake adjustment.

A review of minutes of the Commercial Vehicle Safety Alliance meetings suggests that the reasoning behind the current system of defining defective brakes under the brake adjustment criteria is based on estimating the influence of brake adjustment on the stopping capability of the vehicle being inspected. The intention is that vehicles lacking sufficient stopping capability (because of improper brake adjustment) such that they are likely to cause an accident or contribute to the loss of control of the vehicle by the driver should be placed out-of-service.

NTSB DATA

A review of roadside inspection data revealed that the NTSB data was the only source that includes pushrod stroke measurements on all brakes inspected—those that were in violation as well as that were not in violation. None of the State databases contained information on brakes that were not in violation of the readjustment limits. The NTSB data also include data on the brake chamber size. This is essential for relating the stroke measurement to the out-of-service criteria. The level of detail covered in the NTSB database is sufficient to support calculations of braking capability using the brakeability method.

Most of the NTSB data [4] were collected in roadside inspections performed between March and December 1990. During that period, the NTSB inspected brakes on 1,520 trucks in five States: Florida, Illinois, Oregon, Pennsylvania, and Texas. After the data collection was complete and an analysis performed, additional data was gathered to verify the first round of data collection and to test alternative brake inspection procedures. The supplemental round of data collection on 823 vehicles occurred between April and July 1992 at sites in Michigan, Oregon, Pennsylvania, and Texas. [5] Both sets of data (a total of 2,343 vehicle inspections) were analyzed for this paper.

The NTSB selected trucks for inspection by randomly picking trucks entering weigh stations, such that every Nth five-axle combination vehicle was chosen (N was chosen to keep the inspection teams continuously busy without tying

up the flow of vehicles). Truck configurations included straight trucks pulling one trailer, and tractors with one or two trailers. The teams collected data primarily related to the brake system. Data included company type and size, the make and model year of all units, trailer body type, brake type, chamber size, pushrod stroke measurement for each brake, whether or not the vehicle was equipped with a retarder or limiting valves, and several other brake-related items.

Data collection sites were on interstate and non-interstate roads in order to get a good representation of the types of vehicles in use. Table 1 shows the number of interstate and non-interstate inspections per State.

Table 1. Number of trucks inspected by State and road type

State	Non Interstate	Interstate	Total
Florida	185	107	292
Illinois	197	151	348
Oregon	148	92	240
Pennsylvania	220	152	372
Texas	160	108	268
Subtotal	910	610	1,520
Supplementary data			
Michigan	48	0	48
Oregon	125	130	255
Pennsylvania	145	115	260
Texas	140	120	260
Subtotal	458	365	823
Total	1,368	975	2,343

Though it is not possible to determine in a rigorous manner the extent to which the population of trucks included in the NTSB inspection is representative of the national population, there do not appear to be any obvious biases in the sampling procedure or in the sample itself. Distributions from the NTSB brake adjustment sample were compared with distributions from the 1987 Truck Inventory and Use Survey (TIUS) conducted by the Bureau of the Census. Only a limited number of comparisons were possible. Nevertheless the NTSB sample reasonably matches the national population in the TIUS on some important variables. These variables included trailer cargo body type and tractor model year. For-hire carriers were somewhat over-represented in the NTSB data compared to TIUS, as were conventional truck tractors. However, the cab type and the private/for-hire distinction were not found to be associated with brake adjustment problems.

Overall, the NTSB teams found very high levels of brake violations. Of the 2,343 vehicles inspected, 1,408 (60.1 percent) were placed out-of-service for brakes and other violations. (Although the NTSB teams focused on brake violations, they responded to obvious violations in other areas.) A total of 1,319 (56.3 percent) were coded with brake violations (including non-adjustment related) severe enough to place the truck out-of-service. Considering only brake adjustment related problems, 1,655 (70.6 percent) had at least one brake with a violation and 1,068 (45.6 percent) of the inspected trucks were placed out-of-service.

METHODOLOGY

The purpose of the analysis was to assess the ability of the 20-percent rule to separate vehicles according to their stopping capabilities. A mechanical analysis of the brake system is used to develop the relationship between brake adjustment and stopping capability. Based on this analysis, two methods of assessing the loss of stopping capability due to brake misadjustment are developed. These are referred to as the "demerit" and the "brakeability" methods. A third method of assessing stopping capability is a brake efficiency calculation procedure discussed by R. Heusser in "Heavy Truck Deceleration Rates as a Function of Brake Adjustment"[6].

The NTSB inspection data was processed using the demerit method, the brakeability method and the braking efficiency method to provide a sound and practical comparison between the approaches. Using the brakeability method, the 20-percent rule was evaluated to determine if it adequately screens out trucks with insufficient braking capability. The braking capability was calculated for all NTSB inspection reports on vehicles equipped with S-cam brakes. The vehicles were then divided into two groups based on whether or not they were placed out-of-service under the 20-percent rule.

Distributions of the braking capability for out-of-service vehicles and those vehicles that were not placed out-of-service show that there is a significant overlap between the two groups. While none of the trucks with inadequate stopping capability (defined as 80 percent or less of the braking capability when all of the brakes are fully adjusted) passed the 20-percent rule, a significant portion of the out-of-service trucks had braking capabilities in excess of 80 percent of that available for the fully-adjusted case.

MECHANICAL ANALYSES OF STOPPING CAPABILITY

This section describes the fundamental relationships between brake adjustment, static stroke, and brake temperature. A theoretical-empirical model was developed based upon mechanical modeling of the physical phenomena occurring in the braking system. This model is based on a model developed by Mark Flick in "The Effect of Brake Adjustment on Braking Performance"[7]. Coefficients, describing pertinent mechanical properties of the brakes are evaluated to match experimental data.

Many of the concepts presented later in this paper are based on an understanding of occurrences associated with the operation of brake chambers when brakes are out-of-adjustment. The following discussion uses a series of four questions to help outline or describe basic concepts involved in determining the influence of brake adjustment on stopping capability, particularly stopping distance.

First, to provide an overview, consider the question: Where does the stroke go? The pushrod in the brake chamber moves in response to an increase in air pressure in the brake chamber. As indicated in Figure 1 (taken from reference [8]), the brake shoes contact the drum at 5 or 10

psi. This typically corresponds to approximately 0.5 inches of stroke for a well-adjusted brake. As the brake lining wears, the stroke at which the shoes touch the drum will increase. If the brake is not adjusted, the increase in stroke will continue until the brake no longer provides effective braking action.

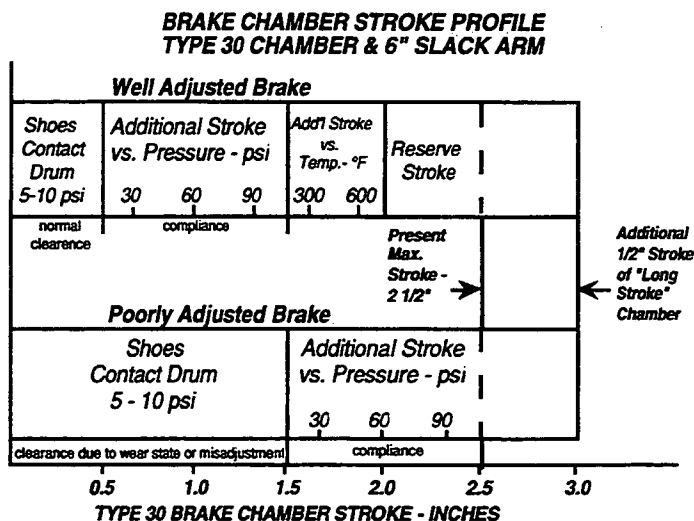


Figure 1. Profile of stroke consumption

Once the linings touch the drum, the stroke increases by about an inch as the air pressure increases to 100 psi. As shown in Figure 1, this would account for the stroke being 1.5 inches when the brakes are cool. Due to drum expansion, more stroke is needed at higher brake temperatures. Stroke can increase by about 0.1 inches per 100°F. The range of temperature from approximately 200°F to 700°F in Figure 1 corresponds to an increase of approximately 0.5 inches of stroke. At elevated temperatures, even a well-adjusted brake may be at the readjustment limit of 2 inches for the example given in Figure 1. For the poorly-adjusted brake in Figure 1, the pushrod would "bottom-out" in the brake chamber and there would be no reserve stroke at elevated temperatures. The additional clearance due to lining wear or misadjustment of the poorly adjusted brake can cause the brake to bottom-out at high pressures.

Up to this point, the discussion has covered the following phenomena: (a) the "pushout pressure" for the linings to touch the drum; (b) the compliance of the linings, shoes, etc. when the linings touch the drum and the application pressure increases, and; (c) drum expansion due to temperature.

To further develop these concepts, a quantitative approach is used to answer the question: How does a brake chamber work? To aid in answering this question, Figure 2 illustrates (a) the output force characteristics of an air chamber (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

adjuster length, is included in this representation of the compliance.

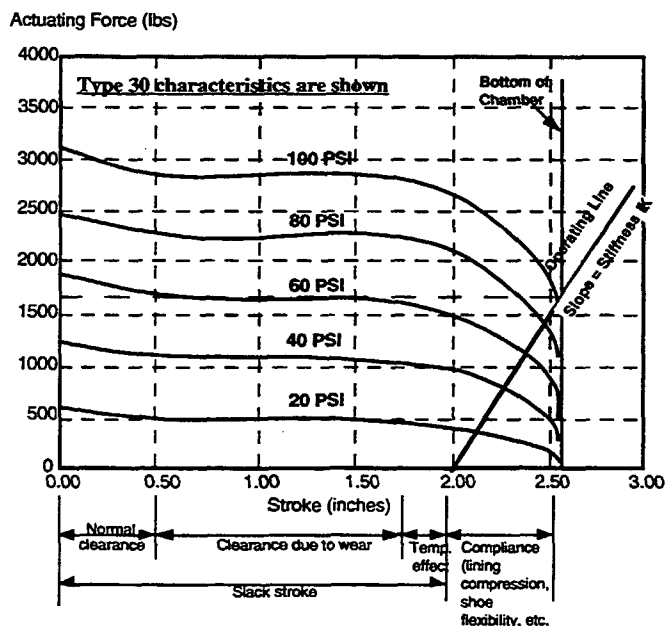


Figure 2. Operating line superimposed on brake chamber characteristic curves

In the example shown in Figure 2, the brake is poorly adjusted. The brake has an initial "slack" of 2.0 inches (the pushrod must travel 2.0 inches in order for the linings to contact the drum). In this example the temperature rise is about 250°F resulting in about 0.25 inches of slack stroke. 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 1,700 pounds. The 1,700 pound force 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. For the example given in Figure 2, there has been a reduction of approximately 60 percent in the actuating-force capability for the brake compared to the fully-adjusted condition. This reduction is due to the amount of overall slack which determines where the lining first makes contact with the drum, and hence where the operating line starts in Figure 2.

Given the above quantitative information, the next question is: How are these conditions represented? A mechanical model for representing the conditions associated with the onset of bottoming-out of the pushrod in the brake chamber and the compliances in the brake was used in the study. As illustrated at the top of Figure 3, the model consists of three elements:

- (1) a pushrod with an actuating force equal to the chamber pressure, P_C , times the chamber area, A_C , and the return springs,
- (2) a non-linear bottoming effect represented by a stroke at which this effect starts, S_C , and non-linear stiffness that increases as stroke, S , increases beyond S_C , and
- (3) a "lining model" which represents the operating line introduced in Figure 2 and consists of the overall slack

S_L , and the stiffness, K_L . (The overall slack, S_L , is the amount of stroke needed for the lining to touch the drum.)

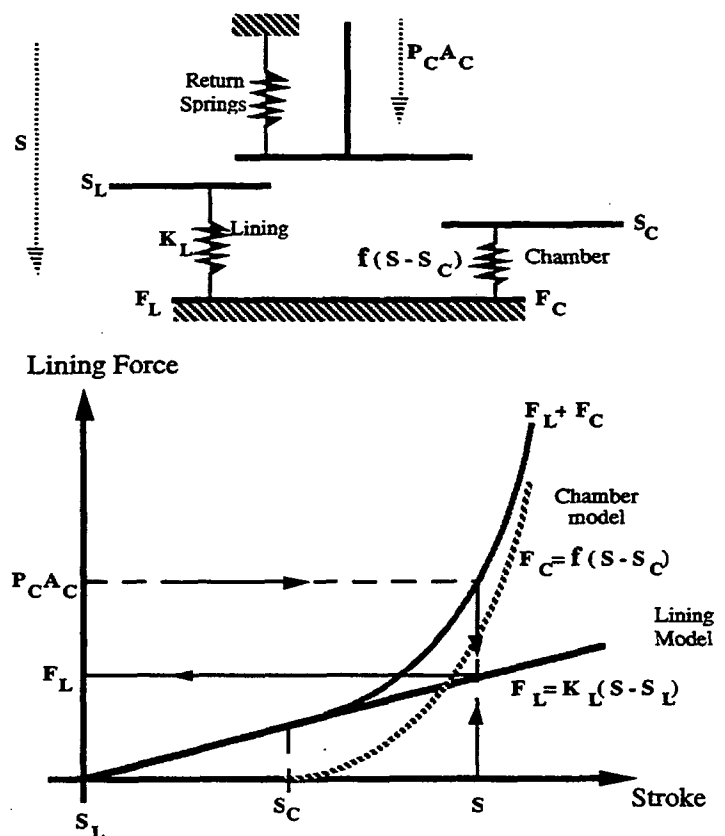


Figure 3. Mechanical model of the brake chamber

Since the overall slack, S_L , changes with temperature during stopping, the model has two inputs—the chamber pressure, and that component of S_L that changes with temperature. The pushrod stroke in combination with the stiffness for the lining and the chamber (as indicated in Figure 3) produces two forces— F_C , the bottoming force of the chamber, and F_L , the actuating force on the lining. The output of the model is the actuating force F_L .

Since the model contains non-linear elements and the overall slack, S_L , changes during a stop, the calculation of the actuating force, F_L , is dependent on a series of calculations. This series or sequence of calculations is indicated by the arrows and dashed lines in the graph at the bottom of Figure 3. At a given instant the slack, S_L , can be computed from the temperature and the thermal properties of the drum. This means that the relationship between the total force ($F_C + F_L$) and the stroke, S , is known. Given the value of the total force on the pushrod (the product of air pressure in the brake chamber, P_C , and the area of the chamber, A_C), the total-force function can be used to solve for S . (That is, $P_C A_C = F_C + F_L$.) Once the stroke, S , is determined the lining model can be used to calculate F_L , the actuating force that is effective in producing brake torque. This series of calculations is illustrated in Figure 3 for a situation in which $S > S_C > S_L$.

The final question considered is: How are the models of individual brakes incorporated into a method for predicting stopping distance? In that regard the model described above

during the inspection) compared to the braking capacity available when the brakes are fully adjusted? A computed value of 1.0 represents a truck with fully adjusted brakes.

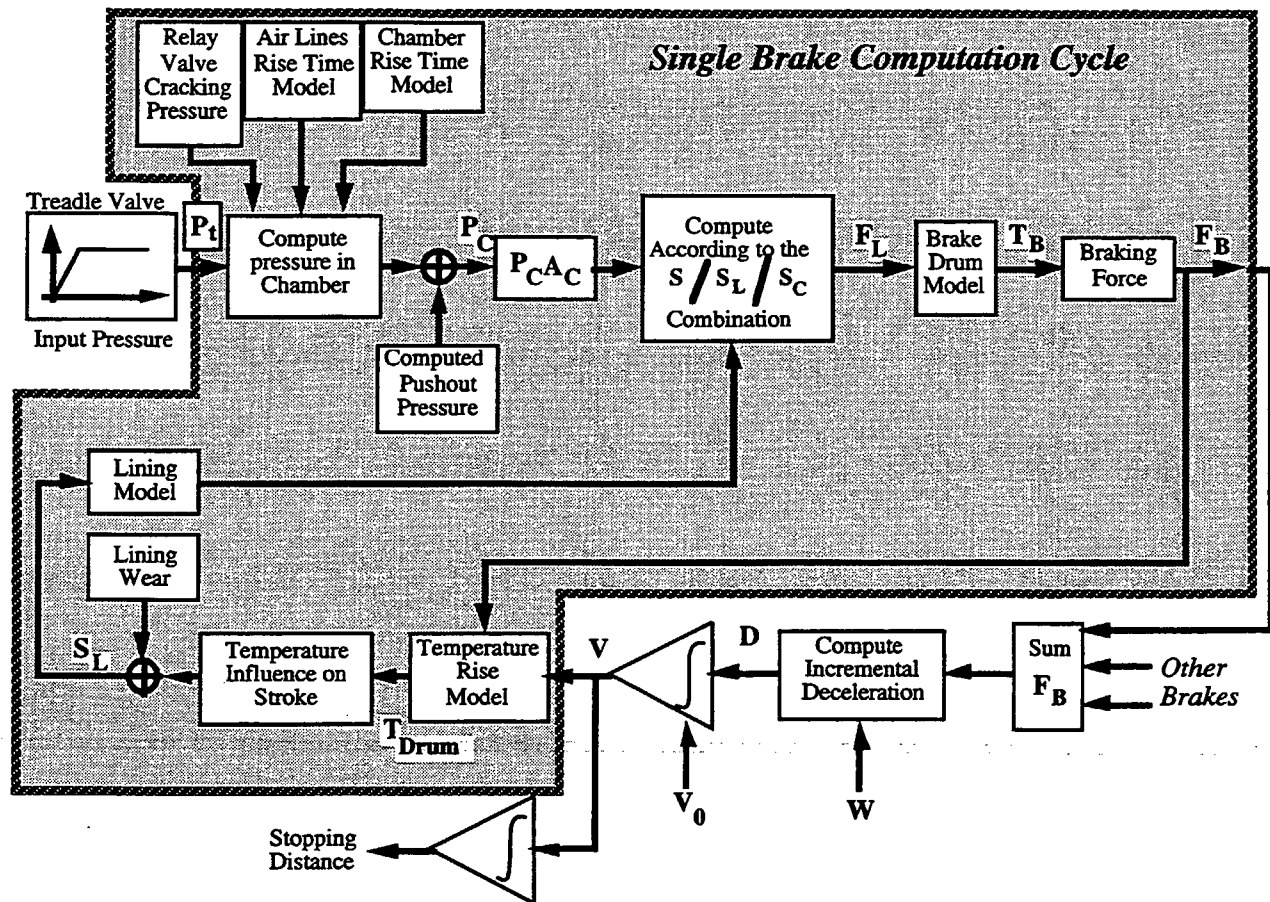


Figure 4. Calculation of stopping capability

may be embedded into a method for calculating stopping distance. The method includes computations of (a) the chamber pressure for each brake, (b) the brake torques due to the actuating forces on the linings of each brake, (c) the temperature rise at each brake, and (d) deceleration, velocity, stopping distance of the vehicle as indicated in Figure 4. Figure 4 illustrates how these separate computations fit together to represent braking on a high coefficient of friction surface. In this case the 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 can be used to predict the influences of various patterns of brake adjustment levels on the stopping capability of a heavy truck loaded to its maximum weight capacity, W .

MECHANICAL ANALYSES OF BRAKE ADJUSTMENT

Two methods were developed to evaluate brake adjustment levels on heavy trucks. The "demerit" and "brakeability" methods are based on the assumption that the components of the brake system (e.g., brake chambers, slack adjusters, etc.) are appropriate and in working order. Both methods are aimed at estimating the amount of loss of braking capability due to improper adjustment of the brakes. They address the question: what portion of the braking capacity is available (at the adjustment levels observed

If, for example, either the brakeability or the demerit value for a certain truck is 0.75, the truck has lost 25 percent of its original stopping capability. A primary difference between the brakeability and demerit methods is the accuracy with which the calculation takes into account the physics involved in the operation of the brakes. The demerit method has less resolution because it uses a single brake adjustment factor for a range of stroke increment. The brakeability method, on the other hand, uses stroke continuously and represents the components of the brake system more rigorously.

DEMERIT METHOD

The idea behind the demerit method is to assign brake adjustment factors to various ranges of brake adjustment. These factors are used to estimate changes in stopping capability for any given level of brake adjustment. In this context vehicles might be placed out-of-service if the estimated decrease in stopping capability was 20 percent. The brake demerits would be associated with the influence of adjustment level on the brake's torque capability. The idea behind the method for determining the desired brake adjustment factors for various ranges of brake adjustment is based on examining brake chamber characteristics.

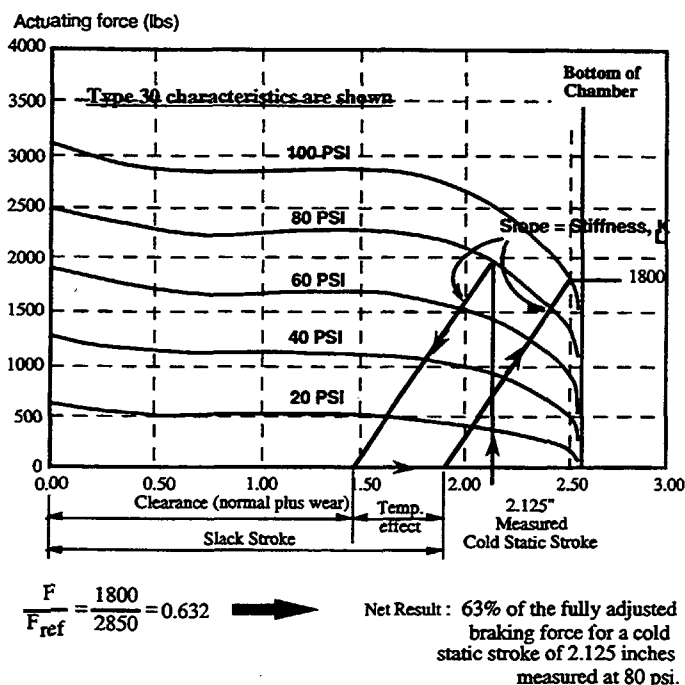


Figure 5. Determination of a brake adjustment factor

To illustrate the ideas underlying the demerit method, the following discussion applies the procedure illustrated graphically in Figure 5 to situations representing various states of brake adjustment.

Table 2 provides the results of carrying out this process for different ranges of cold-static stroke measurements. The brake adjustment factors are based upon an empirical fit to the results of brakeability computations for the 21,460 brakes inspected by NTSB[6]. (The results of fitting the demerit results to the brakeability results are illustrated and discussed later in conjunction with Figures 11 and 12) Since the brakeability results are the best prediction available for estimating stopping capability, the brake adjustment factors are selected to provide the best estimate of the braking capability of the vehicle if the demerit method is used.

For example, a brake close to the readjustment limit has an adjustment factor equal to 0.77 and a brake that is completely backed-off has an adjustment factor equal to zero. Relating the demerit method to the current 20-percent rule, the brake adjustment factors for the 1/2 defective brake case (a brake that is at the readjustment limit or less than 1/4 inch beyond the readjustment limit) and the 1 defective brake case (a brake that is 1/4 inch or more beyond the readjustment limit) are 0.70 and 0.55 respectively. (Please recognize that different results will be obtained when brake chambers with characteristics that differ from those given in Figure 5 are used. Also, different results will be obtained if the static stroke is measured at 90 psi or some other pressure instead of at 80 psi.)

Table 2. Brake adjustment factors

Range of cold-static strokes RL = readjustment limit	Brake adjustment factor
"Fully-adjusted" stroke, S	1.00
$RL - 1/8\text{-inch} \leq S < RL$	0.77
$RL \leq S < RL + 1/4\text{-inch}$	0.70
$RL + 1/4 < S < RL + 1/2\text{-inch}^*$	0.55
$RL + 1/2\text{-inch}^* \leq S < \text{bottom-out}$	0.40
Bottom-out point = S	0.00

* Use 1/2-inch for Type 30 brake chambers. Use the bottoming out distance - 1/8-inch for other types of brake chambers. For example, the bottom-out distance for a type 20 chamber is about 2 3/8 inches.

Based on the brake adjustment factors in Table 2, if all of a vehicle's brakes were close to the readjustment limit, the vehicle would be capable of approximately 77 percent of the braking capability available when all of its brakes are perfectly adjusted. This is basically consistent with the idea that the vehicle's adjustment level is deemed to be unsafe when the braking capability is 80 percent or less of that with fully adjusted brakes.

An assumed axle load is used as the weighting parameter. A 5-axle tractor-semitrailer combination is assumed to have a maximum allowable gross combination weight of 80,000 lbs: 12,000 lbs on the front axle, and 34,000 lbs on each of the two tandem axles. The benefit of using axle weights is two-fold: the inspection process is simplified because the slack adjuster length does not need to be measured; and a sounder basis for comparing the demerit and brakeability methods is provided.

Three of the divisions are in the region of the pushrod travel that is most sensitive to brake adjustment. More divisions would improve the accuracy somewhat, but would be more difficult to apply. At least theoretically, the results from the demerit method should (on the average) produce results comparable to those produced by the brakeability method. Furthermore, if stroke is measured with a resolution of 1/4 inch, results from the demerit method can be expected to be quite similar to those produced by brakeability calculations. Differences in the type of brake chamber (e.g., Type 16, Type 24, etc.) must be taken into account because they each have different torque capabilities in the fully-adjusted state and each have different readjustment limits. A table similar to Table 2 would be used for each type of brake chamber.

The following example, presented in Table 3, illustrates the calculation of the braking capability for a 3-axle (6-brake) truck. In this example four of the brakes are fully adjusted, one rear brake has a cold-static stroke of $RL + 1/8$ inch, and one brake has a cold-static stroke of $RL + 3/8$ inch. When the relative axle loading is not taken into account, the braking capability is 0.88. With the relative axle loading, the braking capability is 0.85. Looking at the relative torque column in Table 3, the total relative torque for this vehicle with all brakes fully adjusted would be 5. This total takes into account that the steering axle brakes (brake numbers 1 and 2) have approximately half the torque of the

other brakes on the vehicle. Under the current 20-percent rule this truck would be placed out-of-service (1.5 defective brakes out of the six brakes on the vehicle is approximately 25 percent defective brakes).

Table 3. Example of the calculation of stopping capability

Brake Number	Adjustment Levels	Adjustment Factors	Relative Torque
1	Fully adj.	1.00	0.50
2	Fully adj.	1.00	0.50
3	Fully adj.	1.00	1.00
4	Fully adj.	1.00	1.00
5	RL+1/8-inch	0.70	0.70
6	RL+3/8-inch	0.55	0.55
TOTAL		5.25	4.25
Adjust. factor		$5.25/6 = 0.88$	$4.25/5 = 0.85$

BRAKEABILITY METHOD

The brakeability method is aimed at obtaining a value that represents the relative braking ability of the truck as a whole. Conceptually, this method is an enhancement of the demerit method. Both methods involve an evaluation of the percentage change in stopping capability of a truck due to its brake adjustment status, but the brakeability involves more complicated calculations and yields more accurate results.

The concepts illustrated in Figure 5 and used in the explanation of the demerit method, also serve as the basis for understanding the brakeability method. Where the demerit method uses brake adjustment factors for certain ranges of stroke to approximate the degradation of braking capacity, the brakeability method employs algebraic calculations involving locally linear equations and intersecting points to obtain more accurate results.

Looking at the model illustrated in Figure 3, the slope of the operating line represents the stiffness of the braking system (symbolized by K_L in Figure 6). This stiffness is determined by the following parameters: the effective length of the slack adjuster; the torsional stiffness of the cam shaft, the effective radius of the cam; the flexibility of the brake shoes and their pivot points; the radius and width of the brake drum; and the stiffness of the lining. Experimenting with the model in Figure 3, two representative values for the slope of the operating line can be obtained. These stiffness values—1,620 lbs/inch for front brakes and 3,120 lbs/inch for rear brakes—were determined to have sufficient accuracy to match the influence of brake pressure on stroke as illustrated in Figure 1. As the length of the slack adjuster is implicitly included in the stiffness, certain lengths of slack adjusters were assumed to be used with certain brake chambers. However, that assumption does not impose any restriction on the accuracy of the brakeability method since the slope of the operating line is modified in the calculations when a slack adjuster length found during the inspection differs from the assumed length.

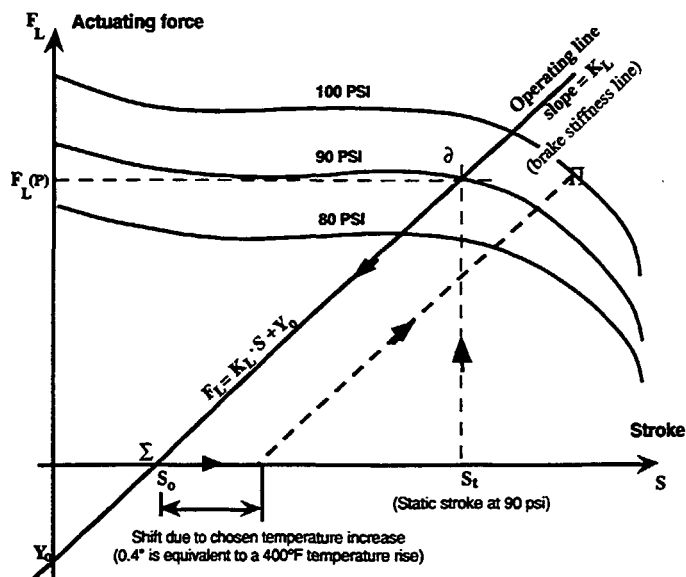


Figure 6. Determination of the operating line's equation

For each brake, the actuating force can be determined by using the appropriate chamber-data table. This is done by using the measured stroke and the pressure at which the inspection was performed, and looking up the corresponding actuating force. With the assumed slope (1,620 lbs/in or 3,120 lbs/in according to the location), once that force-stroke point is established (1 in Figure 6), the equation for the line can be determined and the slack stroke (2 in Figure 6) can be computed. To account for the temperature effect on the stroke, the equation for a parallel line is computed. An additional look-up and interpolation process is used to determine point 3 in Figure 6, and subsequently the available actuating force. The brakeability of the individual brake is determined by the ratio between the resultant actuating force and the maximum actuating force that can be generated by the particular chamber.

After the brakeability of each brake is determined, the total brakeability of the truck is calculated. In doing so, axle loads are used as weighting factors (similar to the demerit method). The total weighted calculation of the brakeability is shown in equation (1).

$$\eta_t = \frac{\sum_{i=1}^{\text{\# of brakes}} \eta_i \cdot \bar{W}_i}{80,000} \quad (1)$$

where:

η_t is the total brakeability of the truck
 η_i is the brakeability of an individual brake
 \bar{W}_i is the individual wheel load (6000 lb. for front wheels, 8500 lb. for rear ones)

RESULTS AND FINDINGS

The results and findings presented in this section address the following question: Does the use of the brake adjustment criteria under the 20-percent rule accurately distinguish between trucks with insufficient braking capabilities and those with sufficient braking capabilities? Ideally, the out-of-service criteria should readily separate vehicles by their braking capabilities. Vehicles placed out-of-service would be expected to have lower braking capabilities than those that are allowed to continue in service. However, the use of the brakeability method for evaluating brake adjustment indicates that the out-of-service population overlaps with the population of vehicles that is not placed out-of-service. A significant percentage of vehicles placed out-of-service for only brake adjustment violations have braking capability exceeding 80 percent of their braking capability with fully adjusted brakes. Trucks with more than 80 percent of their brakes working properly have been considered safe per the 20-percent rule and traditional recommendations concerning the readjustment limit.

The NTSB inspected a total of 2,343 trucks. Of these, 196 had no front axle brakes or had some brakes that were either disc or wedge. Since the focus of this study is on S-cam brakes, those 196 vehicles were eliminated. One truck had an unusual brake chamber size for which the UMTRI brakeability value could not be calculated, so it too was eliminated. These deletions leave 2,146 trucks, which were used in the statistical analysis. Of these 2,146 trucks, 936 had sufficient brake violations, considering just brake adjustment, to be put out-of-service.

Figure 7 shows the distribution of vehicles put out of service (OOS) and those that were not OOS by the UMTRI brakeability measure. Overall, the 20-percent rule divides the truck population into reasonably distinct groups. Vehicles that passed the 20-percent rule had a mean brakeability of 0.94, with a range of 0.82 to 1.00 and standard deviation of 0.036. The average brakeability for vehicles placed out-of-service was 0.78 with a range of 0.24 to 0.93 and a standard deviation of 0.105. A test of the difference of means was significant at better than 0.0001 indicating that there is only a 0.0001 chance of observing two means this different from the same distribution. None of the vehicles that passed the adjustment criteria had a brakeability below 0.8 (80 percent of the braking potential if all of the brakes were fully adjusted). Therefore, all trucks with an insufficient braking capability (measured by brakeability) failed the 20-percent rule.

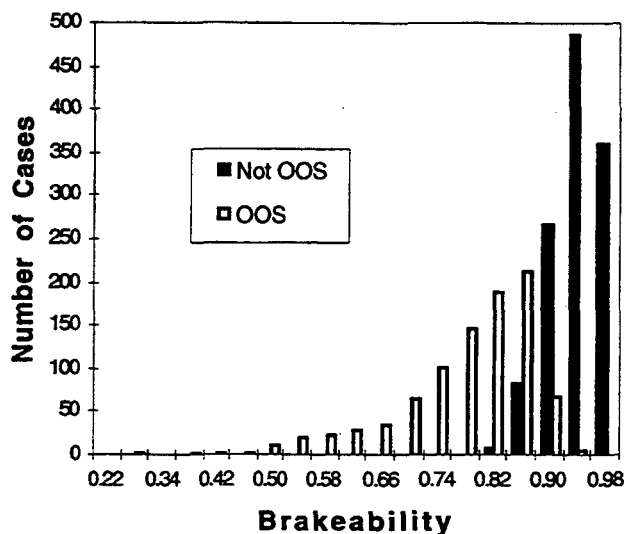


Figure 7. UMTRI brakeability values for NTSB data

While none of the trucks with a brakeability below 0.8 passed the 20-percent rule, many trucks with a higher brakeability failed the brake criteria. Table 4 shows the breakdown of the NTSB inspection data. Of 936 trucks placed out-of-service for brake adjustment, 480 (51.3 percent) had adequate braking, as indicated by brakeability values greater than 0.8. Keep in mind that for the purposes of this study, the 20-percent rule for placing vehicles out-of-service is based solely on the brake adjustment criteria. Violations such as grease on the linings or drums, cracked drums, or problems with air pressure are not considered. Thus the 480 out-of-service trucks with adequate braking can be considered "false positives," cases where the 20-percent rule incorrectly indicated a problem. There were no "false negatives," cases where the 20-percent rule incorrectly indicated adequate braking capability.

Table 4. UMTRI brakeability values for vehicles under the 20-percent rule

Status	Brakeability score		Total
	<.8	>=.8	
Not OOS	0 (0.0)	1,210 (100.0)	1,210 (100.0)
OOS	456 (48.7)	480 (51.3)	936 (100.0)
Total	456 (21.2)	1,690 (78.5)	2,146 (100.0)

A large proportion of the false positives failed the inspection solely on the basis of brake adjustment. Only 170 of the false positives had other out-of-service violations, including other brake violations. Approximately one-third (310) of the vehicles classified as out-of-service due to brake adjustment had adequate braking and no other violations detected, though this result is tempered by the fact that the NTSB inspections focused on brakes and not other vehicle problems.

At this point in the discussion, the NTSB measure of

braking efficiency is also worth considering. Braking efficiencies are calculated by a procedure described by Heusser[6]. The NTSB braking efficiency measures are calculated in a manner similar to brakeability, but the values are normalized to an estimate of available friction. The scatter plot of the NTSB efficiency measure and the UMTRI brakeability measure in Figure 8 shows that the measures are similar but not identical. The NTSB braking efficiency values used were calculated assuming brake temperatures of 400°F and 80,000 pounds gross vehicle weight, which are the same temperature and loading assumptions used for the brakeability calculations. Braking efficiency shows a greater range of values, between 0.02 and 1.00. The braking efficiency values are highly correlated but not collinear.

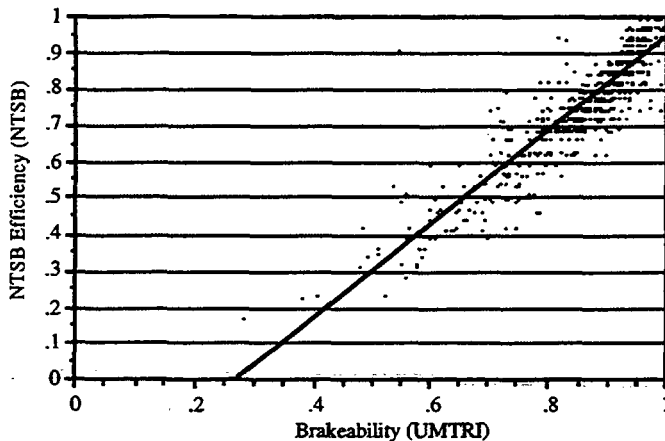


Figure 8. NTSB-calculated braking efficiency by UMTRI brakeability including regression line

Figure 9 displays the NTSB-calculated braking efficiency for vehicles examined during the NTSB study. This figure is comparable to Figure 7 for brakeability. The peak (greatest number of cases with the same braking efficiency value) of the out-of-service trucks is well below 0.8, while the peak braking efficiency value for those vehicles that passed the 20-percent rule is well above 0.8. The mean braking efficiency for the out-of-service vehicles is 0.63. The mean braking efficiency for vehicles which passed the 20-percent rule was 0.86. (1,383 trucks had both NTSB-calculated braking efficiencies and only S-cam brakes.)

Figure 9 illustrates the overlap of the out-of-service population with the population of vehicles passing the 20-percent rule. The overlap illustrated for the NTSB braking efficiency is greater than the overlap for the UMTRI brakeability (shown in Figure 7). Note that both of the braking measures show some degree of overlapping populations. The amount of overlap for each figure can be estimated by converting the bar charts into curves and calculating the area that falls under both curves. The brakeability score separates the two populations best with only 15.7 percent overlap. For the braking efficiency values, the overlap is 24.7 percent. The braking efficiency measure, since it includes considerations that are not directly related to brake adjustment, is not as closely related to the 20-percent rule as brakeability. Also, while the 20-percent rule identifies populations that are, on average, different

with respect to braking capabilities, the criteria results in some vehicles being placed out-of-service with greater braking capability than that of some of the vehicles that pass.

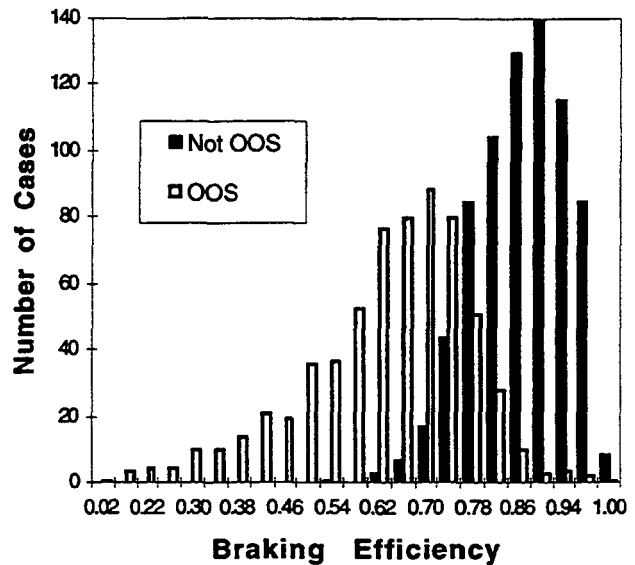


Figure 9. NTSB braking efficiency at 80,000 lb. and 400°F OOS using 20-percent rule only

The structure of the 20-percent rule provides opportunities for false positives since each brake is given the same weight as all other brakes and the range of stroke measurements are classified into three categories. Two examples illustrate how trucks with good brakeability values can fail the 20-percent rule.

A typical pattern is a truck with each steering axle brake at 1/4 inch beyond the readjustment limit and all other brakes properly adjusted. The two defective brakes would represent 20 percent of the brakes on a five axle combination vehicle and therefore the vehicle would fail the 20-percent rule. However, the steering axle brakes bear the smallest share of the braking load and are typically activated by Type 16 or Type 20 brake chambers. Therefore, the improper adjustment of steering axle brakes has only a small practical effect. It should be emphasized that these results in no way suggest that steering axle brakes do not have an impact on the braking ability of heavy vehicles, only that two steering axle brakes which are slightly out-of-adjustment are not as detrimental to braking ability as other out-of-adjustment brakes.

Another frequent pattern is a vehicle with four brakes just at the readjustment limit, and all other brakes fully adjusted. The four brakes at the readjustment limit count as two defective brakes under the 20-percent rule, yet in many instances the brakeability value for the vehicle is greater than 0.8.

As described previously, brakeability represents the percentage change in stopping capability of a vehicle due to its brake adjustment status. It basically answers the question: If the inspected truck with some of its brakes out-of-adjustment were fully laden, what stopping capability

would it have relative to the same truck with its brakes fully adjusted? Or equivalently, how much braking force could its brakes generate given its current adjustment status, relative to the braking force produced with its brakes fully adjusted?

Brakeability assesses the braking ability of the subject truck based only on its brake adjustment status, normalized to fully adjusted conditions. Other parameters that are not related to brake adjustment are not considered. Braking efficiency as computed by the NTSB and as explained in "Heavy Truck Deceleration Rates as a Function of Brake Adjustment" [6], incorporates considerations that are not necessarily brake-adjustment related. It is based on the premise of wheel locking ability; the closer the truck is to locking all of its wheels, the higher the efficiency.

In concept, both brakeability and braking efficiency start off in a similar manner. Based on the geometries involved (such as slack adjuster length, drum diameter, etc.), the current adjustment status at each brake is considered to evaluate chamber-bottoming effects and the resultant losses of braking force. From this point the two methods proceed in different directions. The efficiency computes drag (the lesser between braking force and a sliding tire), and normalizes it to the assumed road friction of 0.56. By contrast, brakeability normalizes the available braking force to that which is obtained with fully adjusted brakes. No limited adhesion considerations are made.

As for a comparison between the brakeability and demerit methods, they are conceptually similar. Both are aimed at estimating the amount of loss of braking capability due to out-of-adjustment brakes. One of the primary differences between the two methods is the extent to which the brake system hardware and geometrics are accounted for. To provide a sound, practical comparison between the two methods, the NTSB inspection data was processed using both methods.

By virtue of the more detailed and comprehensive computations involved with the brakeability method, it was considered more accurate than the demerit method. The brakeability method was therefore used as a baseline for evaluating the accuracy of the results obtained by the demerit method.

The demerit method uses brake adjustment factors to account for the degradation of braking ability over certain ranges of stroke. The NTSB data was also processed using the demerit method, and the results compared with those obtained using the brakeability method. By evaluating the resultant plots both qualitatively and quantitatively, an assessment of the accuracy of the demerit method was made. The brake adjustment factors as listed in Table 2 were found to be the best combination for accuracy and practicality.

The comparison of the demerit and brakeability methods is illustrated in Figure 10. Using the brake adjustment factors from Table 2, the demerit results from the NTSB inspection data are shown with the results obtained by using the brakeability method. Applying the concept of placing vehicles out-of-service under the 20-percent rule, particular attention is focused on the demerit and brakeability values around 0.8. Figure 11 provides a magnified view of the graph in the area between the 0.7 and 0.9 values.

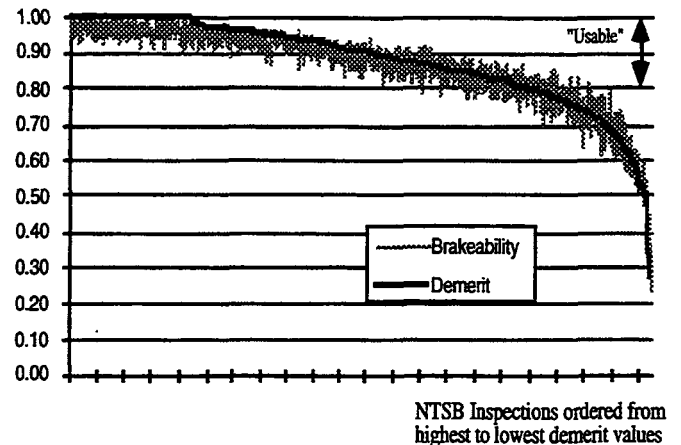


Figure 10. Demerit and brakeability results for the NTSB data

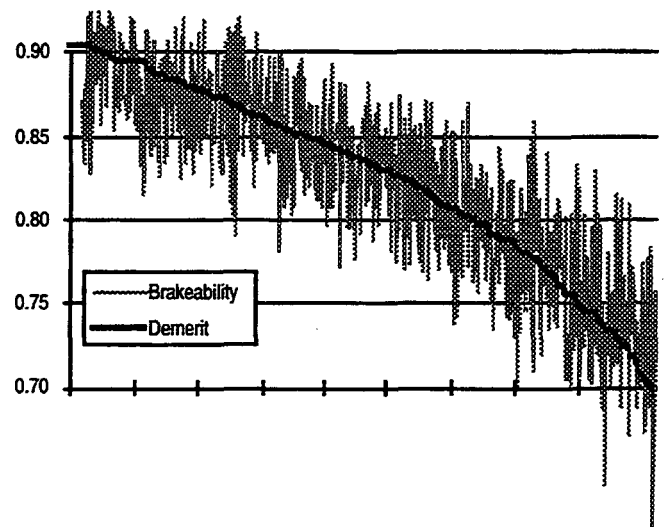


Figure 11. Demerit and brakeability results for the NTSB data — 0.7-0.9 values

Several observations can be made from Figures 10 and 11. First, Figure 10 resembles a plot of the characteristic output force versus stroke for a brake chamber. Using that mechanically-sound analogy, those trucks that would be placed out-of-service (below the 0.8 value for the demerit and brakeability methods) are well into the area where the output force for the chambers drops off rapidly. Trucks above the 0.8 value line are positioned in the area where the output force for the chamber is acceptable and will not be placed out-of-service. Second, the degree to which the demerit method values agree with those of the brakeability method around 0.8 is relatively high.

In order to further investigate the conformity level between the demerit and brakeability methods, the values obtained for the NTSB data were plotted against each other. The plot is shown in Figure 12 with the equation of the linear fit line. The R^2 value of 0.944 indicates a high level of correlation between the demerit and brakeability results. As with Figure 10, the area around the 0.8 value is of particular interest. Figure 13 provides a magnified view. The plot in Figure 13 is divided into quadrants:

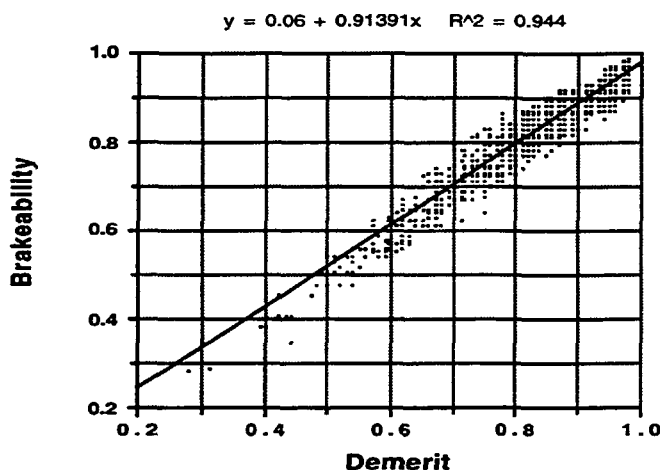


Figure 12. Demerit vs. brakeability results of the NTSB data including regression line

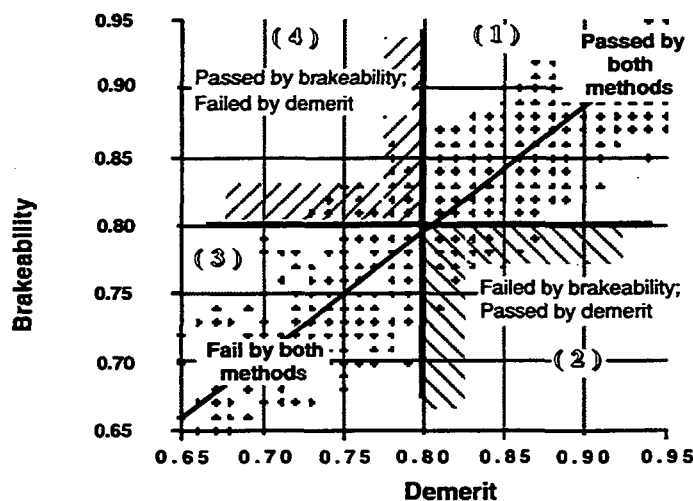


Figure 13. Demerit vs. brakeability results of the NTSB data including regression line — 0.65-0.95 values

- Quadrant 1 - 1,671 vehicles out of the total of 2,146 vehicles (77.9 percent) represent trucks that would have passed under both the demerit and brakeability methods;
- Quadrant 2 - 61 out of the 2,146 vehicles (2.8 percent) represent trucks that would have passed using the demerit method and placed out-of-service using the brakeability method;
- Quadrant 3 - 371 out of the 2,146 vehicles (17.3 percent) represent trucks that would have been determined out-of-service by both the demerit and brakeability methods;
- Quadrant 4 - 43 out of the 2,146 vehicles (2.0 percent) represent trucks that would have been placed out-of-service using the demerit method and passed using the brakeability method.

Assuming that the brakeability method is the more accurate way to evaluate a vehicle's stopping capability

based on its brake adjustment, applying the demerit method to the NTSB data would result in 3.52 percent false negatives (vehicles with inadequate braking capability passing the inspection— $100 \cdot (61) / (61 + 1671) = 3.52\%$) and 10.39 percent false positives (vehicles with adequate braking capability being placed out-of-service— $100 \cdot (43) / (43 + 371) = 10.39\%$).

Currently, the brake adjustment of heavy trucks is being evaluated under the 20-percent rule. Up to this point, three alternative methods were introduced as substitutes: (1) NTSB's braking efficiency, (2) UMTRI's demerit, and (3) UMTRI's brakeability. The last section summarizes conclusions and recommendations.

CONCLUSIONS AND RECOMMENDATIONS

The findings and results of this study indicate that the 20-percent rule as currently applied results in placing a number of vehicles with adequate braking capability out-of-service. Some of these vehicles have braking capability that is more than 80 percent of that available if the vehicle would have had all of its brakes fully adjusted. This means that some of the vehicles placed out-of-service have more braking capability than some of the vehicles that are allowed to continue operating. The costs associated with removing vehicles from their transportation mission are large. The FHWA and the CVSA should consider revising the out-of-service criteria in order to reduce the incidence of placing vehicles with adequate braking capability out-of-service.

The basis for considering a change in the out-of-service criteria is associated primarily with the idea that the de facto goal has been to use 80 percent of the fully adjusted braking capability as the criteria. Currently, the 20-percent rule is less precise than one might consider necessary to do a uniform and appropriate job in attaining that goal. A detailed analysis of over 2,100 inspections of five-axle trucks indicated that employing the 20-percent rule results in many trucks being placed out-of-service even though they have more than 80 percent of their fully adjusted braking capability. If the goal of reducing the number of false positives for brake adjustment is accepted, we recommend that the following ideas be considered in revising the criteria.

Two alternative approaches to determine brake adjustment criteria are the brakeability and demerit methods. Both provide inspection practices that are more uniform, technically sound, and appropriate than the 20-percent rule. In order to evaluate brakeability, the inspectors need to use a computer to be efficient and accurate, while tables and a calculator will suffice when using the demerit method (although a computer would also be more efficient for the demerit method).

If long term planning concerning brake adjustment data collection and analysis and a high level of accuracy are critical considerations, the brakeability method is recommended. Once computers are in use for the brakeability method, other tasks (either current or future improvements) carried out at the inspection site might be incorporated into the brake inspection program. If needed, modifications to the data fields (for example, information on

new types of brake chambers) or algorithm can easily be implemented. Also, the analysis described in this paper could be extended to larger samples if the stroke measurements from MCSAP inspections were recorded.

If, on the other hand, immediate improvement of the results is the primary goal for which a small sacrifice in accuracy is acceptable, the demerit method may be the best option. The tables used for the demerit method can be prepared in a short time, and with the assumption that calculators are readily available for the inspectors, the demerit method could be implemented quickly. An alternative approach: implement the demerit method immediately while developing the long-term program for utilizing the brakeability method in the future.

In practical terms, if computers are employed, the inspector would need to enter the stroke measurements, the chamber sizes, and the slack adjuster length. The computer would perform the calculations to determine the out-of-adjustment and out-of-service violations. Although it may not seem unreasonable to ask inspectors to gather this information, it would require more time than inspectors currently spend. However, the time and effort would not be equivalent to that of the NTSB inspection teams since the information the MCSAP inspectors would need is only a fraction of that gathered by the NTSB.

In summary, the current 20-percent rule for brake adjustment provides a good initial indication of the amount of loss in stopping capability for heavy trucks. Recently published Federal regulations on automatic brake adjusters and brake adjustment indicators should help to improve the problem of brake adjustment on heavy trucks. The use of automatic brake adjusters will reduce the frequency with which brakes are out-of-adjustment while the use of brake adjustment indicators will help to make the detection of out-of-adjustment brakes much easier for drivers.

However, there are more technically sound means of evaluating stopping capability which can be applied more uniformly across the spectrum of possible brake adjustment situations. The benefits of changing the criteria would be (1) stricter criteria with regard to those vehicles that are placed out-of-service, (vehicles with a completely backed-off brake that now pass the criteria would no longer pass if the braking capability of the vehicle is less than 80 percent of that for the fully adjusted case), and (2) fewer false positives.

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