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SAE Technical
Paper Series

861942

Tractor and Trailer Brake System Compatibility

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Truck and Bus Meeting and Exposition
King of Prussia, Pennsylvania
November 10-13, 1986

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ISSN 0148-7191

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Printed in U.S.A.

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ABSTRACT

This paper serves as the seventh report in a series of reports on NHTSA's Heavy Vehicle Brake Research Program and deals with the subject of tractor and trailer brake system compatibility. It provides a detailed definition of compatibility, discusses the factors that influence it and presents data and analyses which indicate the degree of compatibility in the heavy duty combination vehicle fleet at large. The paper suggests ways in which compatibility can be improved so that combination vehicle brake systems will be more durable and provide an enhanced level of safety.

IN 1979, THE NATIONAL HIGHWAY Traffic Safety Administration (NHTSA) initiated a research program on heavy duty vehicle braking at its Vehicle Research and Test Center (VRTC) in East Liberty, Ohio. Since that time, VRTC has conducted a great deal of research aimed at improving heavy duty vehicle braking system performance. Previous reports (1,2,3,4,5,6)* published by NHTSA have documented VRTC's efforts in a number of areas related to heavy duty vehicle braking.

Because of the current interest and activity within the Society of Automotive Engineers (SAE) relative to tractor and trailer brake system compatibility it was decided to publish this report on compatibility, the seventh report in the series, as an SAE paper.

Compatibility is the ability of tractor and trailer braking systems to function well together and provide desirable overall combination vehicle braking performance. It is a popular topic in the trucking industry and has been since the fifties when various committees were established to study compatibility problems. In any discussion of heavy duty vehicle braking systems that occurs, the subject almost always comes up and it usually receives considerable attention. In the 1980's there has been a major focus on compatibility to the extent that various industry organizations such as the SAE, the American Trucking Associations (ATA), the Truck Trailer Manufacturers Association (TTMA), the Motor Vehicle Manufacturers Association (MVMA) and others have devoted entire meetings or technical sessions to compatibility and/or have set up special committees to deal with the various aspects of compatibility. In addition, several years ago, TTMA, MVMA and ATA formed the Truck Trailer Brake Research Group (TTBRG) in order to focus research efforts on heavy duty combination vehicle braking performance. The TTBRG immediately placed compatibility at the top of their list of subjects requiring attention.

In general, truck users are not satisfied with the present state of affairs as it relates to compatibility and have encouraged manufacturers to improve the situation. The NHTSA, concerned about the safety aspects of compatibility, has been conducting compatibility research at its VRTC for several years. The purpose of this effort (part of the agency's overall Heavy Vehicle Brake Research Program) is to determine the extent of safety related compatibility problems and to recommend solutions.

The paper which follows provides an in-depth, detailed definition of compatibility, discusses the factors that influence it and presents and analyzes data from tests conducted by VRTC. It is intended to show the degree of compatibility existing in the heavy duty combination vehicle fleet and to identify the effects of compatibility on maintenance (durability) as well as on safety. It is also intended to show ways in which compatibility can be improved.

WHAT IS COMPATIBILITY?

In the broad sense, compatibility refers to the ability of tractor and trailer braking systems to function together in harmony to provide the combination vehicle with a braking system that: [1] requires minimum maintenance (is

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*Numbers in parenthesis indicate references listed at end of paper.

0148-7191/86/1110-1942$02.50

durable) and [2] exhibits a safe level of braking performance. Although the trucking industry is concerned about the safety aspects of compatibility, much of the focus is on the durability aspects of compatibility. This is primarily because poor durability is the most visible result of poor compatibility. If the braking system on a tractor or trailer is doing more than its share of the braking, it will wear out faster. The result of poor compatibility becomes obvious very quickly to the truck user in terms of excessive brake lining and drum wear, brake drum cracking, the need to adjust brakes more frequently, etc. on the "over braked" unit in the combination.

The safety aspects of poor compatibility are more subtle since resulting poor limit braking performance only becomes a problem in crash avoidance maneuvers that are not everyday occurrences. In addition, if a crash occurs, there are so many contributing factors, it may not be obvious to the truck user that poor braking performance may be a significant causal factor.

Fortunately, as will be shown later, improving compatibility can result in significant improvements in <u>both</u> durability <u>and</u> safety if proper care is taken in addressing the problem. One of the purposes of this paper is to emphasize the need to understand both aspects of compatibility and to address them simultaneously so that solutions to compatibility problems will, in effect, be complete in the broadest sense.

BRAKE FORCE DISTRIBUTION

Compatibility from both a safety (or limit braking performance) and a durability standpoint can be shown to be a direct function of brake force distribution among the various axles in combination vehicles. Figure 1 shows brake force versus time plots for a hypothetical two axle tractor coupled to a single axle trailer during a typical brake application. Each of the three brake force versus time plots can be broken down into three regions: [1] apply transient, [2] steady state (or sustained) braking and [3] release transient.

In an actual brake application, the steady state region may not be a constant level as shown in Figure 1. In fact, in a short "snubbing" of the brakes by the driver, a steady state region may not even exist. Brake forces may come up to a maximum or peak level and then immediately decline. On the other hand, in a long low level brake application to control vehicle speed on a grade, the brake forces may be at a relatively constant level for a longer time period than implied in Figure 1. In any event, it is not the absolute shape of the curves that determines compatibility but the <u>relative</u> positioning of the various axle brake force curves with respect to one another. How this relationship affects durability and safety will be explained next.

EFFECT ON DURABILITY -- It is obvious that brake force distribution among various axles determines the brake work distribution during a brake application. Brake work is simply brake force times braking distance. If an axle has a higher force it will do more work since all axles travel the same distance. Because brake wear is a function of the work that the brake does, brake forces must be distributed according to the ability of the brakes to handle the resulting work distribution, otherwise, unequal wear will occur. Consider the simple example of two axles that have identical brakes but do not do the same amount of work during braking because of differet actuating air pressures; over a period of time, the brakes doing the most work will wear out faster and require more frequent adjustment. In addition, the brakes that do more work tend to run at higher brake temperatures and this compounds the problem. It is a well known fact that brake lining wear rate is a function of temperature as well as brake work. Research by Fancher (7) shows that brake lining wear increases as temperature increases (for a given amount of work). This increase can be quite significant at the relatively high brake temperatures that can occur when the brakes are used continuously or repeatedly with little cooling time between applications. Unusually high brake temperatures can also cause drum cracking or even brake fires.

EFFECT ON SAFETY -- Poor durability caused by poor compatibility has an indirect effect on safety. Brakes that wear faster require more maintenance (more frequent adjustment and more frequent replacement of components). If this maintenance is not performed, the brake system may be unable to develop the braking force needed in emergency situations.

There also are several direct safety consequences of poor compatibility, as well. In a limit braking maneuver, the wheels on an axle with too much braking force can lock up prematurely causing loss of tire side force capability. If the front axle wheels lock up, it will not be possible to steer the vehicle although it will travel straight ahead in a stable fashion; if tractor drive axle wheels lock up, the tractor will tend to spin or yaw and a jackknife could result; if trailer axle lockup occurs, the trailer will tend to swing and may intrude into one or more adjacent traffic lanes.

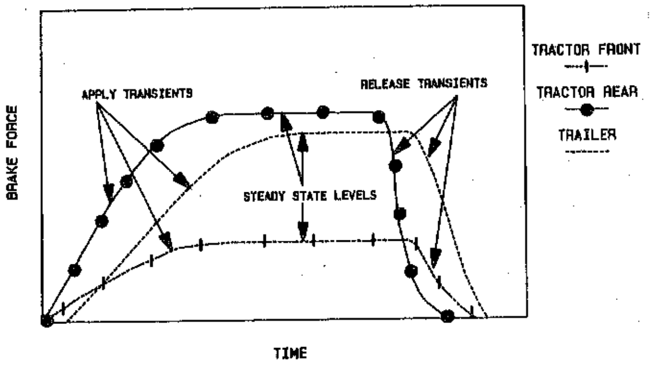

Fig. 1 - Tractor and trailer brake forces versus time for a hypothetical combination vehicle during a typical brake application

Ideal brake balance (and compatibility), from a vehicle stability and control standpoint, exists when the brake force distribution is equivalent to the normal force distribution. The amount of brake force that an axle can develop before wheel lockup occurs is limited by the product of the normal force times the tire/road coefficient of friction; therefore, since the coefficient of friction is essentially the same for all axles, lockup of all axles simultaneously depends upon the brake forces being proportional to the normal forces. In this case, maximum deceleration can be achieved before lockup occurs.

Referring to Figure 1, the steady state brake force levels shown are those that could potentially result in wheel lockup since this is where maximum braking is achieved and maintained. It is, therefore, critical that these levels be distributed according to axle normal forces.

Steady state brake force distribution is determined by the steady state brake control line pressure input versus brake force output relationship that exists at each axle. Figure 2 shows such a relationship for the hypothetical three axle combination vehicle shown in Figure 1. For each axle, the control line pressure input versus brake force output relationship is determined by the pneumatic system characteristics and the foundation brake effectiveness (brake torque versus actuating pressure). In order to determine steady state brake force distribution, the control input air pressure level must be known; then the corresponding brake forces can be determined as shown in Figure 2.

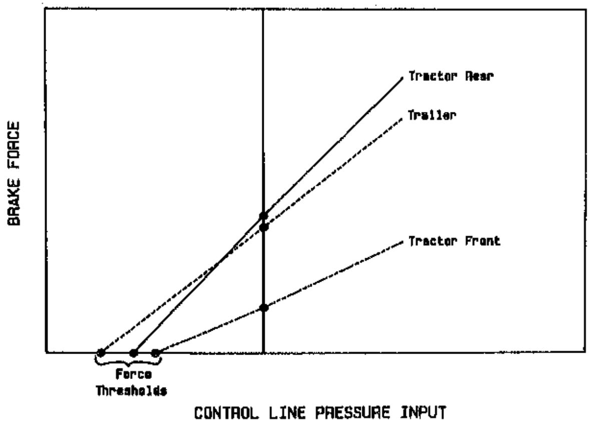

Fig. 2 - Steady state brake forces as a function of control line pressure input for a hypothetical vehicle combination

It should be noted that although brake force versus control pressure relationships are usually linear, or close to linear, they do not necessarily intersect the x-axis (control line pressure input level) at the same point or threshold level. The ratios of the force levels are not constant; they change as control input level changes. At relatively high levels of control input, brake force distribution approaches a constant since the effect of the brake force thresholds is minimized.

Normal force on an axle during braking is the static weight on the axle plus or minus any weight transfer that occurs during braking as a result of inertial effects; this normal force during braking is commonly referred to as the "dynamic weight" on the axle. When brake force distribution is equivalent to dynamic weight distribution, the vehicle will be able to achieve the maximum possible deceleration on a surface without the occurrence of wheel lockup. When wheel lockup does occur, all wheels will lock up at the same control input level (assuming all brakes have sufficient torque to lock wheels on the particular surface).

Ideal compatibility in terms of maximum deceleration capability, stability and control under all loading and/or operating conditions cannot be achieved without the use of proportioning valves. Since dynamic weight distribution changes with static vehicle loading as well as deceleration during braking, brake force distribution must vary as a function of these parameters. Referring to Figure 2, the relative positioning of the various axle brake forces would have to change each time vehicle loading and deceleration changes.

In Europe, braking regulations (8,9) require that brake force distribution on combination vehicles be relatively close to ideal. As a result, devices have been developed for European vehicles which vary brake force distribution as a function of axle normal force. These devices are commonly referred to as load sensing proportioning valves. Such valves usually are not used on U.S. vehicles; the typical U.S. brake design practice is to use a fixed brake force distribution which can only be ideal at a given vehicle loading and deceleration rate. Performance at other operating points will be less than ideal. Nominal U.S. practice is to select the brake force distribution that is optimum for the fully loaded vehicle during low decelerations. In effect, this produces a brake force distribution that is equivalent to the distribution of the vehicle gross axle weight ratings (GAWRs). Unfortunately, when the vehicle is empty and decelerating at any rate or is loaded and decelerating at a high rate, less than ideal brake balance exists.

FMVSS 121, Air Brake Systems, contains requirements for minimum brake performance on an axle as a function of the axle's GAWR and as such defines the minimum level that the brake force versus control line pressure input levels must exceed. FMVSS 121, however, places no upper limit on this performance. There are no other regulations, standards or design guidelines that set this upper limit. Therefore, if a trailer manufacturer, for example, decides to exceed this minimum by a significant margin and a tractor manufacturer works with smaller margin, the brake force distribution will not be equivalent to the GAWR distribution. The impact that this has on stability and control will be discussed later.

Although the effect of brake force threshold levels on brake force distribution is minimal in high pressure brake applications, the effect can become significant in low level, sublimit braking situations where differences in thresholds can result in safety problems. For example, referring to the hypothetical case in Figure 2 where the trailer threshold is relatively low, if the input level applied to the brake system is just high enough to apply only the trailer brakes, the trailer brakes will do 100 percent of the braking work. The likelihood of this occurring in normal low level braking situations (i.e., for gradually stopping the vehicle or controlling speed at a constant level on grades) increases as the threshold difference increases. As long as the driver can develop the desired braking force from the trailer only, without reaching the input level to initiate tractor braking, he will continue to use only the trailer brakes and will be unaware that the tractor is not braking. This situation will obviously result in more wear on the trailer brakes. Additionally, if the vehicle's brakes are used continuously or repeatedly, the trailer brakes will become very hot. Ultimately, depending on the length of the grade, the trailer brakes could fade (or possibly even disintegrate or catch fire). Of course if they fade (i.e., lose effectiveness), it is possible for the driver to apply a higher input level to initiate tractor braking to make up for the trailer fade. If a panic or emergency stop is required for some reason, the braking force of the trailer will not be available and an accident could result due to inadequate total braking necessary to stop the vehicle. The effect of threshold differences on safety will be discussed in more detail later as well.

Up to this point only the steady state brake force balance has been discussed. Transient brake force balance is also important. Referring again to Figure 1, transients occur during brake application and release. These transients are primarily determined by the pneumatic timing or speed at which the air pressure in the brake chambers at each axle builds or decays.

Pneumatic timing plays an important role in the performance of air brake systems since the generation of brake force and the resulting vehicle deceleration rate are directly related to the air pressure available in the brake actuating chambers. Pneumatic application time, defined as the time required for the brake chambers to reach a relatively high pressure level after the driver applies the brake control, affects vehicle stopping distance. The sooner that air pressure builds in the brake chambers, the sooner the vehicle is able to reach its maximum deceleration rate and the shorter the vehicle's stopping distance. In combination vehicles, the application time of each unit also affects the coupling forces between the units. Consider the case of a tractor semitrailer; if the application time of the trailer brakes is very long compared to that of the tractor brakes, the tractor will begin generating braking force before the trailer. During the time period before the trailer brakes apply, the tractor will be decelerating its own mass plus the entire mass of the trailer. When this occurs there is a peak compressive force at the tractor to trailer coupling. In effect, the tractor is decelerating the trailer via the force it imposes on the trailer's kingpin without any assistance from the trailer brakes. Another way of viewing the situation is that the trailer "overruns" the tractor when only the tractor brakes are applied. Once the trailer brakes apply, the force at the kingpin drops due to the fact that the trailer brakes now provide a portion of the forces necessary to decelerate the trailer's mass. Since the brakes on a semitrailer cannot provide all of the braking for the trailer (i.e., only about one half of the semitrailer's weight is carried by the braked trailer axles) the kingpin force does not drop to zero but remains at some reduced, but still substantial, level. In effect, trailer "overrun" still exists even when all brakes are fully applied, however, the level of the "overrun" force is lower.

Obviously, high compressive coupling forces during braking on any type of articulated vehicle are undesirable from the standpoint of stability. If the combination is negotiating a turn when the brakes are applied, the towed unit will impose a force on the towing unit that creates a destabilizing moment about the towing unit's center of gravity. If the towing unit's tires cannot generate enough side force to resist this moment, skidding will occur and a jackknife may result. In order to minimize compressive coupling forces, pneumatic application times should be such that brakes on trailing units apply at the same time or slightly before brakes on the towing units. Although it is possible for a combination vehicle with mismatched timing to achieve a "balanced" condition by slowing down the faster unit, such an approach is not as desirable since it degrades vehicle stopping distance capability. A much more effective approach, if possible, is to speed up the slower unit so that the overall combination vehicle application timing is at a minimum level. In a typical combination vehicle, the trailer is the limiting factor in determining application timing since its brakes are further from the brake control (treadle) valve than the brakes on the tractor.

Drivers apparently are able to sense an application timing mismatch between tractors and trailers in normal everyday braking situations. When tractor brakes are too fast applying with respect to trailer brakes, drivers tend to complain about trailer "bumping", "overrun" or "run-up" and clearly feel the characteristic is undesirable. Many vehicle manufacturers and component suppliers over the years have had to contend with such complaints. Reference 10 documents some recent work that was performed in one fleet where such complaints were made. In this case, the apparent solution to the driver complaint problem was to slow down the application time of the tractor brakes to reduce the timing mismatch.

The safety implications of the "bumping" complaints are not totally clear. Reference 5 provides vehicle test data that shows that relatively large application time differentials were necessary before significant levels of degradation in vehicle stability could be detected. Although test drivers could sense lower levels of timing mismatch in terms of undesirable vehicle "feel" these levels did not appear to produce handling problems. However, the undesirable feel to the driver may make him wary of applying the brakes quickly or may encourage him to use the trailer hand valve only in emergency situations. Continual complaints from drivers can be troublesome for truck owners and manufacturers, therefore, minimizing the application timing mismatch between tractors and trailers appears to be a worthwhile goal regardless of the stability implications.

Pneumatic release timing, defined as the time required for the pressure in the brake chambers to fall to a relatively low level equivalent to a brake release after the driver releases the brake control, also affects vehicle stability. If a driver, attempting to stop a vehicle, locks its wheels (causing the vehicle to begin to skid), immediate release of the brakes is necessary if the driver is to regain control. Therefore, release timing should also be as fast as possible. Release timing of each unit in a combination vehicle, just like application timing, affects the coupling forces between the units. If the trailer release timing is equal to or slower than the tractor release timing (the latter is typically the case) there is no increase in compressive coupling forces. Release of the brakes while decelerating will actually result in a reduction in the compressive coupling forces that exist during braking. If the tractor brakes completely release while the trailer brakes are still applied, the coupling forces will actually go into tension, producing a stabilizing effect. If for some reason, however, the tractor brakes release after the trailer brakes, compressive coupling forces generated will increase. For maximum stability, an articulated combination vehicle's towing unit brakes should release at the same time as or before a towed unit brakes.

In summary, the above discussion on transient brake force balance indicates that "fast" application and release of brake force is desirable to minimize stopping distance and avoid excessive wheel lockup; but, for optimum combination vehicle stability during braking, the timing relationship between units should be such that brakes on towing units do not apply before or release after the brakes on towed units. Fast release of the brakes also reduces brake wear.

OTHER FACTORS THAT DETERMINE COMPATIBILITY

As the above discussion indicates, brake force distribution (steady state and transient) lies at the heart of compatibility. Although there are a number of other vehicle factors that must be considered to determine compatibility, their effect on compatibility cannot be determined until brake force distribution is known. These other factors are listed in Table 1 in three categories depending upon whether they affect durability only, safety only or both of these aspects of compatibility.

WHAT DETERMINES BRAKE FORCE DISTRIBUTION?

It is important to understand the vehicle factors that establish brake force distribution. They are briefly discussed below.

a) <u>Foundation brake type and size</u> - The type and size brake used on an axle affects the torque and braking force that the brake can generate. By far, the most commonly used brake on heavy duty combination vehicles today is the cam type drum brake. Wedge type drum and disc brakes are also used on combination vehicles but their penetration in the fleet is estimated to be less than five percent. Most vehicles use 16-1/2 x 7 inch cam type drum brakes on tractor drive, trailer and dolly axles and 15 x 3-1/2 inch or 15 x 4 inch cam type drum brakes on steering axles.

b) <u>Brake Lining Frictional Properties</u> - The coefficient of friction of the brake linings also affects the torque that a brake can generate. There are many brake lining formulations used today on combination vehicles and each of these formulations have unique friction properties which can vary as a function of normal force, temperature, rubbing speed, etc. (They also have unique wear or durability properties which do not directly influence brake force).

c) <u>Slack Adjuster Length</u> - Cam type drum brakes use a lever arm, called a slack adjuster, to convert the linear force from the actuator or brake chamber into a torque that turns the cam shaft. The cam which is on the other end of the shaft spreads the shoes in the brake against the drum. The length of the slack adjuster determines the moment on the cam shaft and, therefore, the brake torque that the brake can generate for a given actuator force. Virtually all trailers and dollies use 6 inch slack adjusters. Tractors use 5, 5-1/2, or 6 inch slack adjusters depending upon the vehicle manufacturer's design philosophy.

TABLE 1 -- Vehicle Factors in Addition to Brake Force Distribution That Must be known to Determine Compatibility

<u>Durability Only</u>	<u>Safety Only</u>	<u>Safety and Durability</u>
Drum Wear Characteristics	Load Distribution	Drum Thermal Properties
Lining Wear Characteristics	Center of Gravity Height	Brake Cooling Characteristics
	Tire/Road Coefficient of Friction	Lining Friction Variability
		Lining Fade Properties
		Parasitic Drag*
		Total Load

*Aerodynamic drag, engine drag, driveline drag and tire rolling resistance.

d) Brake Chamber Size - The actuating device that converts system air pressure into force to operate the slack adjuster is called a brake chamber. The effective area of this actuator or chamber determines the actuating force as a function of input air pressure and, therefore, affects brake torque. Most trailers and dollies use type 30 (type indicates effective area in square inches) chambers. Most tractor drive axles use type 24 or 30 chambers; tractor steering axles typically use type 12, 16 or 20 chambers.

e) Adjustment Level - As References 2 and 11 indicate, brake torque is affected by brake adjustment level. Adjustment level determines the stroke required from the brake actuator to apply the brake. Since the actuator force delivered by brake chambers decreases with increasing stroke, adjustment is an important parameter in determining brake force.

f) Pneumatic Valve Characteristics - Pneumatic valves control the air needed by the brake chambers to apply (or release) the brakes. Many different types of valves are used in combination vehicle braking systems. Some of these valves have a major impact on compatibility as a result of how they modify the input pressure level and flow rate (or timing).

g) Pneumatic Plumbing Dimensions - Tubing, hoses and fittings connect all of the reservoirs, pneumatic valves and brake chambers together. Although these components do not affect steady state air pressure level, they do have a significant impact on the brake system apply and release time. Although valve characteristics can also affect timing, it is the length and inside diameter of tubing and hoses that are usually the limiting factors in achieving fast apply and release times. Fitting orifice diameters can also impact timing if they are smaller than the inside diameters of the tubing and hose attached to them.

h) Tire Size - All of the previously discussed factors affecting brake force distribution were related to the braking system. Tires can have an effect as well. Since tire size determines the rolling radius of the tire/wheel assembly, it also establishes the lever arm that converts brake torque into braking force at the tire/road interface. Although tire size has no effect on brake torque distribution (this depends only on brake system components) it does have an effect on brake force distribution. Reducing tire size on one or more axles in a combination will result in more force being generated at the tire road interface on these axles since,

$$T = F \times R \qquad \text{Eq. (1)}$$

$$\text{or } F = T/R \qquad \text{Eq. (2)}$$

where T is brake torque, F is brake force and R is tire rolling radius.

This increased force could result in premature wheel lockup on the axle(s) with the smaller tires. It could also result in the brakes with smaller tires doing more work and running at higher temperatures thereby causing faster brake wear-out.

Figure 3 is a graphical depiction of the factors which affect brake force distribution. It also shows the relationship between brake force distribution and the durability and safety aspects of compatibility. Figure 3, in effect, provides an overall summary of the above discussions.

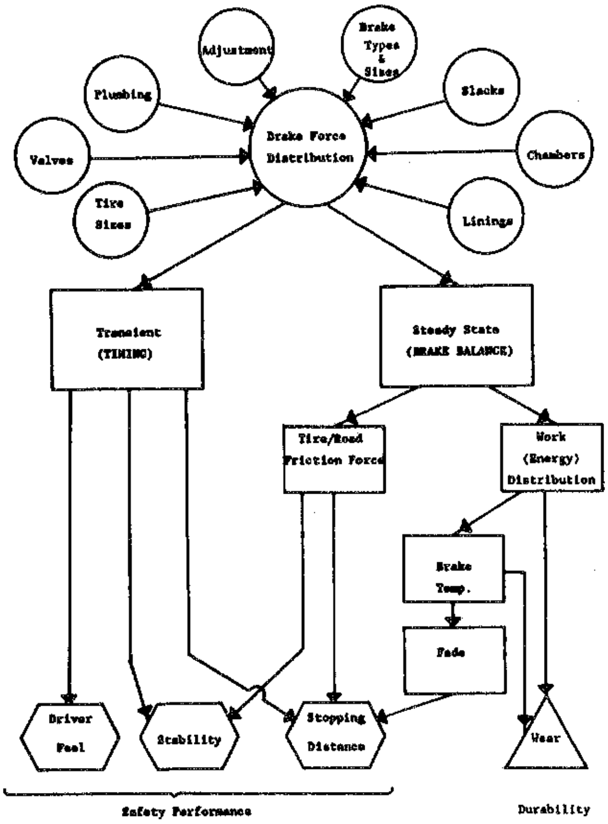

Fig. 3 - Graphical depiction of compatibility factors

WHAT DO AVAILABLE DATA SHOW?

In order to determine the present state of affairs as it relates to compatibility, it is necessary to look at data available on the brake force distribution existing in current vehicles. The most recent and complete set of available data is that which was collected by the VRTC for the TTBRG in support of the SAE Braking Systems Subcommittee's* efforts to develop an SAE recommended practice for compatibility performance requirements to go in concert with the recently developed SAE J1505 test procedure (12). Much of these data, collected in November and December 1985, will be presented in this paper and analyzed in detail.

Nine tractor semitrailers (3-S2's) and six sets of doubles (2-S1-2's) were tested in this program. These vehicles were provided to VRTC for testing by ATA member fleets. They were generally late model vehicles in good condition

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*Subcommittee of the Brake Committee in the Truck and Bus Council.

and had mileages ranging from approximately 1000 -- 200,000 miles. Each combination vehicle was prepared and tested as follows:

Vehicles were received, instrumented and loaded so that axles were at or near their GAWR; "as received" brake adjustment existing at each brake was measured and recorded. Brakes were then fully adjusted and timing tests were conducted. Apply and release timing was determined for the entire combination as a single unit with respect to treadle valve movement and then for each vehicle in the configuration separately according to the procedure specified in Docket 85-07 Notice 1 which is a Notice of Proposed Rulemaking (NPRM) specifying a new method of evaluating timing in vehicles for Federal Motor Vehicle Safety Standard (FMVSS) No. 121, Air Brake Systems.

After timing tests were completed, static or steady state pressure differentials in the pneumatic system were determined. This was done by measuring the pressure in each brake chamber, and the tractor primary and secondary control lines as a function of the trailer control pressure measured at the gladhand between tractor and trailer (control gladhand pressure). The brake control (treadle) valve was applied and released, pausing at discrete pressure levels, by using a screw jack device installed in place of the foot pad and plunger on the treadle valve. After completion of the static pressure differential tests, the control line gladhand pressure corresponding to the torque (and force) threshold at each brake was determined using the SAE J1505 procedure (12).

After completion of the stationary vehicle tests, dynamic tests were run on the test track in accordance with the SAE J1505 procedure. No burnishing was performed -- vehicles were tested with as-received lining conditioning. The SAE J1505 procedure requires that the deceleration produced by the brakes on each axle (or pair of axles in the case of a tandem) be measured at control line gladhand pressure levels of 15, 20 and 40 psi (most of the tests also included 10 psi). The measured decelerations and the total mass of the vehicle were used to calculate brake force (and brake force distribution) as a function of control line pressure. Deceleration resulting from parasitic drag was measured to correct for its effect on the brake force calculations. Finally, an all-brake test (all brakes operational) was run at each pressure level. This provided a check to see if the individual axle results added up to the all-brake results.

STATISTICAL LIMITATIONS -- The test vehicles were not a statistically random sample of the U.S. truck fleet. The data collected and the analysis presented here should be considered in this light. Generally speaking, the vehicles were newer than most of those on the road and were from relatively large fleets that have extensive maintenance programs and logically would have inspected the vehicles prior to submitting them for testing. Therefore, it must be assumed that the vehicles were in better condition than average combination vehicles on the road. Also, in selecting vehicles, there was an attempt to obtain original equipment (OE) componentry. Although some of the vehicles did have aftermarket brake linings, most of the linings, and essentially all other brake system components such as valves, drums, etc, were OE. Reducing the number of components involved should have reduced the variability in test results between vehicles. On the other hand, some of the OE components were low production components that were unique to particular fleet specifications which might inflate the variability "band". For discussion purposes, it will be assumed that the variability seen here is possible in the fleet at large and the effect of this variability on compatibility will be assessed. This may not be sound from a purely statistical standpoint but it provides some useful insights.

AS RECEIVED ADJUSTMENT -- Adjustment is an important ingredient in compatibility because it impacts the force that a brake can generate and thus affects the brake force distribution in the combination.

Table 2 gives a summary of the as-received brake adjustment for the 15 test vehicle combinations. It can be seen from Table 2 that 17 (11.3 percent) of the 150 brakes (10 brakes per vehicle) checked were out of adjustment or beyond the manufacturers recommended limit. The bulk of these (9.3 percent) were those brakes with manual adjusters. Table 2 also indicates that an additional 17 brakes (11.3 percent) were right at the recommended limit. Although these brakes are technically in adjustment, they were at the "ragged edge." References 2 and 11 indicate that brakes at this level of adjustment have significantly reduced torque capability. It is somewhat troubling that 10 (6.6 percent) of the brakes with automatic adjusters were running at the manufacturers recommended limit and that another 3 (2 percent) were actually beyond the limit.

TABLE 2 -- As-Received Brake Adjustment*

	Total No. of Brakes	Beyond Limit	At Limit	Below Limit
Brakes With Auto Adjusters	96	3	10	83
Brakes With Manual Adjusters	54	14	7	33
TOTALS	150	17 (11.3%)	17 (11.3%)	116 (77.3%)

*Checked at 100 psi as per MVMA Truck/Bus/School Bus Inspection Handbook (13).

Recent on-road survey data (14) indicate that the adjustment situation on more representative samples of vehicles is considerably worse. Of the 390 vehicles checked in this survey, the average vehicle had 30 percent of its brakes out of adjustment. It is not possible to tell from these data, however, the breakdown between manual and automatic adjusters.

PNEUMATIC TIMING -- As discussed above, relative pneumatic timing between the tractor and trailer(s) affects the transient brake force distribution and stability of the combination. If tractor brakes apply significantly ahead of the trailer brakes an inordinate amount of trailer "bumping" will occur. If the trailer brakes are slow to release the drivers ability to recover from a wheel lockup situation (and potential trailer swing-out) will be hampered.

Figures 4a and 4b show the apply times for brakes on the tractor semitrailers and doubles, respectively. Time shown is that required to reach 60 psi in the brake chambers measured from first movement of the treadle valve. It can be seen from Figure 4a that all of the 3 axle tractors except tractor number 1 have drive axle (which provide the bulk of the tractor braking) apply times less than 0.2 seconds. Trailer apply times on the other hand range from 0.3 seconds to over 0.5 seconds. Of particular interest are vehicles 2 and 9 where the apply time differentials between the tractor drive and trailer axle brakes are relatively large (0.35 sec on vehicle 2 and 0.40 sec on vehicle 9). It should be noted that in all cases in Figure 4a, the trailer lags the tractor drive by at least 0.1 seconds. Two other sources of data (5,10) indicate that these data are not atypical.

Figure 4b indicates, as expected, that the differentials in apply time for doubles are even greater than for "singles." Differentials between the drive axles and second trailer axles varied from 0.2 seconds to over 0.5 seconds. Reference 5 indicates the existence of even larger differentials (as high as 0.9 sec) for doubles although many of the vehicles in Reference 5 were older models than those shown in Figure 4b.

Release timing for the nine tractor semitrailers are shown in Figure 5a. It can be seen that trailer release times are quite long in four of the nine vehicles, (over 1.0 seconds). Tractor drive axle release times on the other hand were 0.4 seconds or less. Again these data are in line with the data shown in References 5 and 10. Figure 5b shows the release time data for doubles. Surprisingly, the doubles trailer and dolly release times are not significantly different than the single trailer release times in Figure 5a. One reason for this is the presence of quick release valves in the control lines of the trailers used in doubles. FMVSS 121 performance requirements dictate the use of such valves in trailers equipped to tow other trailers. Similar release timing data are shown in Reference 5.

It should be noted that the recent NHTSA Notice of Proposed Rulemaking (Docket 85-07 Notice 1) proposes changes intended to improve combination vehicle pneumatic timing. This

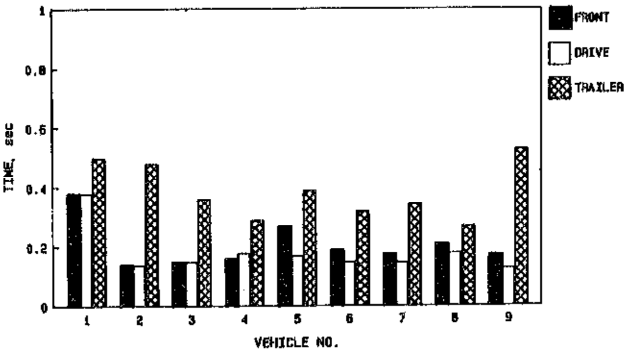

Fig. 4a - Apply time at each axle set -- nine tractor semitrailers

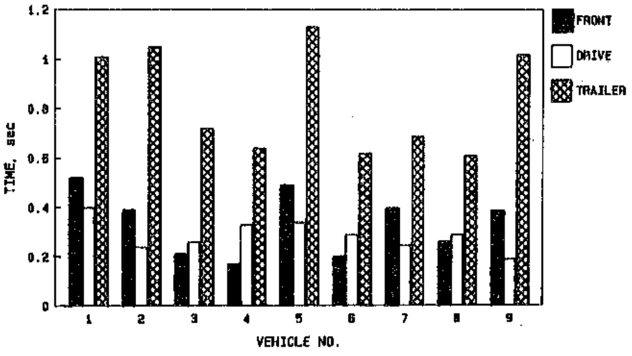

Fig. 5a - Release time at each axle set - nine tractor semitrailers

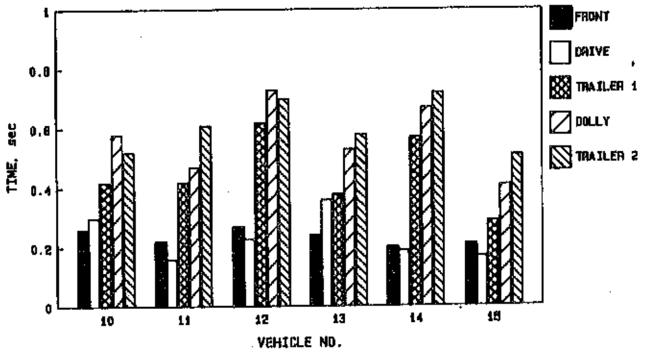

Fig. 4b - Apply time at each axle set -- six doubles combinations

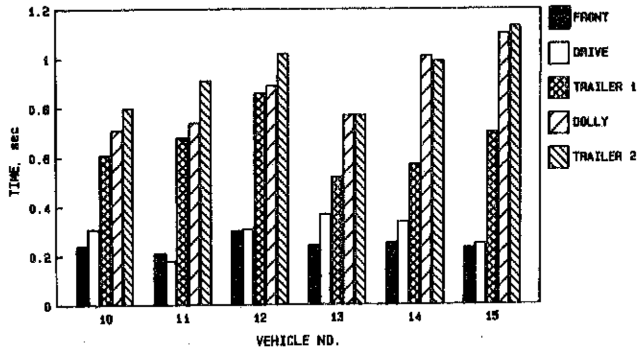

Fig. 5b - Release time at each axle set -- six doubles combinations

Notice proposes minimum tractor gladhand apply and release times (in a 50 in^3 test reservoir) thereby placing requirements on the tractor's ability to deliver and release air from the trailer's control line. Currently there are no requirements on this interface and some tractors are relatively slow in both apply and release at this connection.

The Notice also proposes a new device (or mini tractor) for determining trailer timing performance and proposes modified requirements for trailer apply and release times. The mini-tractor serves as a simulated standardized tractor and is used by trailer manufacturers to certify their trailers to FMVSS 121. The current mini-tractor is not truly representative of actual tractors and results in less than optimum trailer plumbing.

Finally, the Notice proposes a slightly longer maximum brake apply time for tractors (0.50 versus 0.45 seconds) in order to reduce the difference in brake apply time between tractor and trailer(s).

This proposed change, when finalized, should result in faster trailer apply and release times and reduced apply time differentials between the tractor and trailer. As a result, combination vehicle transient brake force distribution, stability and stopping distance capability should be improved.

STEADY STATE PRESSURE DIFFERENTIALS -- Steady state pressure differentials in the pneumatic system do not, per se, provide a measure of compatibility -- it is the steady state brake forces that are important. In fact, looking only at steady state pressure differentials can be misleading. Pressure is an "intermediate" quantity in the chain of events that takes place between the driver applying the treadle valve and brake force being developed at the tire/road interface. This is also true for timing since timing is a measure of how fast pressure rises or falls; however, pneumatic timing is the only convenient means of assessing transient brake force distribution. In the case of steady state brake force distribution, other direct means are available.

Consider the example of a cam type drum brake tractor connected to a wedge type drum brake trailer. It is well known that wedge brakes require higher chamber pressures to begin developing brake torque than cam brakes. If one attempts to balance the brake system by insuring that pressure differentials between the various axles are close to zero, the system will actually be unbalanced at low pressures with the cam brakes doing most of the work. In such a case, some amount of pressure differential is actually desirable. Foundation brake characteristics as a function of pressure must be known for pressure information to be meaningful. If the foundation brakes are similar, the existence of pressure differentials between axles may indicate lack of compatibility. In any event it may also be desirable to determine pressure differentials in order to diagnose a problem no matter what the characteristics of the foundation brakes are. Such an approach can be used to identify a faulty valve that is causing an unbalance in braking force, for example. Given these limitations on pressure differential information and the fact that more direct brake force information was determined for the 15 vehicle sample, pressure differential data collected will not be presented here; only the more useful brake force data will be presented. Pressure data will be utilized in some of the analysis which follows, however.

BRAKE FORCE THRESHOLDS -- It takes a certain amount of input at the brake control valve to initiate brake torque (and brake force) at each wheel. This input level is necessary in order to open valves in the system and to provide a pressure level in the brake chamber that is sufficient to overcome friction in the brake and the force of the brake shoe and brake chamber return springs. Opening of the valves requires overcoming valve internal friction and valve return springs. Valve characteristics as well as foundation brake and brake chamber characteristics are, therefore, important in establishing the input level necessary for the initiation of brake force (threshold pressure).

From a work balance standpoint, brakes on all axles should start to generate force at the same control input level. Brakes that start to develop force at a lower input level than other brakes will do more work and, therefore, overheat and wear faster, particularly in low pressure applications which are quite common in everyday driving. In fact, if the threshold pressure at an axle is lower than at the other axles, the brakes on this axle may be the only ones doing any work at all (i.e., 100 percent of the braking) in low pressure applications. It is, therefore, very important that the input level necessary for the initiation of brake force (threshold pressure) at each axle be determined when assessing compatibility.

SAE J1505 describes the method of making the threshold pressure determination as follows:

> "Determine the control (service) gladhand pressure level at which braking starts to occur at each brake by raising the vehicle and rotating the wheel by hand while gradually increasing input to the brake system (slowly applying the treadle valve). Record the control gladhand pressure level at which brake torque (and force) is first evident. Continue to increase pressure to approximately 40 psi and then slowly decrease it until the point at which the brake is fully released is determined; record the result. The average of these two recorded values is defined as the brake threshold pressure."

Figure 6 provides a graphical definition of the brake threshold pressure. It can be seen in Figure 6 that hysteresis exists in the system and that the release pressure is somewhat below the apply pressure. This is a typical characteristic

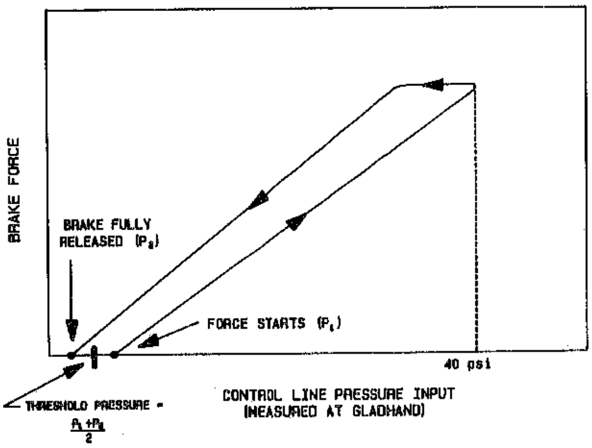

Fig. 6 - Graphical definition of brake force threshold pressure

of air brake systems and is due to hysteresis in the pneumatic valves and foundation brakes. Selection of the average of these two pressures as a measure of threshold pressure was made by the SAE Brake Systems Subcommittee after analyzing test results from dynamic tests where brake force as a function of pressure was measured. Extrapolation of this relationship to zero force shows the threshold pressure to be somewhere between the two pressures near the average value. This is so even though the dynamic data were gathered from constant pressure stops where overshoot was not allowed. Apparently as the vehicle vibrates or "bounces" on the road, the friction in the valves and foundation brakes is "relaxed" and the force-pressure relationship seeks the middle of the hysteresis loop. Otherwise the threshold pressure predicted by the road test results would have corresponded to the apply (torque starts) pressure measured in the static tests.

Table 3 lists threshold pressures for the 15 test vehicles and Figure 7 is a graph of the ranges of threshold pressures found on the axles of the vehicles. In establishing these data the average threshold pressures for the two brakes on a single axle or four brakes on a tandem were used. If individual brake thresholds had been plotted the ranges in Figure 7 would have been even broader since the individual brakes on an axle or axle pair varied somewhat from this average value.

In order to assess the significance of Table 3 and Figure 7 on compatibility, it is helpful to first consider the results of a recent series of tests conducted by VRTC with a three axle tractor coupled to a tandem axle semitrailer.

The purpose of these tests was to determine how differences in threshold pressures between the tractor and trailer affect compatibility. The VRTC test vehicle was specially prepared so that the brake linings on all axles were the same with the tractor drive and trailer axles having the same size brakes (16-1/2 x 7 inch), same size brake chambers (type 30), same length slack adjusters (6 inch) and same relay type valves. Since steering axle brakes on tractors are almost always "smaller" than drive axle brakes no attempt was made to match these brakes with the drive and trailer axle brakes. The steering axle brakes were 15x4 inch with type 16 chambers and 5.5 inch slack adjusters.

After setting up the vehicle, brakes were burnished with a 500 snub burnish; snubs were made from 40-20 mph with 10 ft/sec^2 decelerations at 1-1/2 mile intervals. Brake force distribution was then determined using the SAE J1505 procedure.

This brake distribution test indicated that the trailer axle brakes were developing approximately 40 percent less force for a given control input pressure than the tractor drive axle brakes. This difference in effectiveness was unexpected since brake components on both sets of brakes were very similar with essentially the same threshold pressures. The only major

TABLE 3 -- Threshold Pressures (psi) Determined for Nine Tractor Semitrailers (3-S2) and Six Doubles (2-S1-2)

Combination Vehicle	Front	Drive	Trailer 1	Dolly	Trailer 2
1	8.6	6.6	4.4		
2	11.3	8.4	5.6		
3	5.3	5.6	4.7		
4	5.6	5.0	5.9		
5	11.4	5.2	4.4		
6	12.3	4.9	4.8		
7	9.8	8.4	3.9		
8	15.0	6.2	4.3		
9	10.6	8.8	5.5		
10	5.7	4.2	4.0	3.3	4.0
11	4.5	6.0	4.0	4.0	4.1
12	13.1	4.7	5.7	8.8	5.6
13	7.7	6.6	4.0	4.2	4.0
14	8.8	6.1	5.4	4.2	5.6
15	10.6	5.5	5.4	5.7	7.0

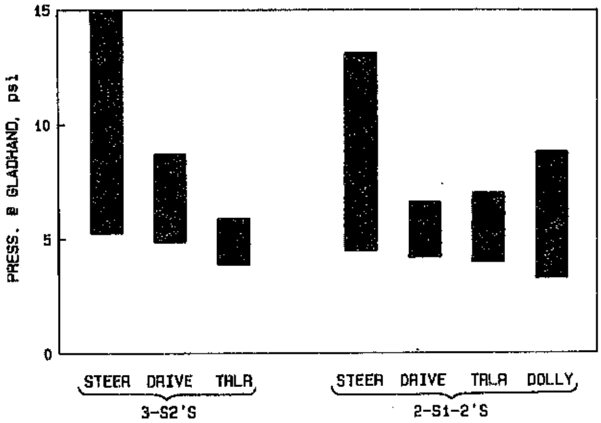

Fig. 7 - Range of brake force threshold pressures measured in nine tractor semitrailers (3-S2) and six doubles (2-S1-2)

difference was the fact that the foundation brakes on the tractor were made by a different manufacturer than those on the trailer. Both sets of brakes were of the same basic type (double anchor pin, S-cam drum brakes).

It was suspected that variation in performance of the linings may have caused the difference. therefore, linings were replaced and burnished and the test repeated. The second test still showed the trailer brake force to be lower but by only 10-23 percent (depending upon control pressure level). It was decided that this was the best balance that could reasonably be achieved and the program continued. A series of tests with different levels of threshold pressure difference between the tractor drive and trailer axle brakes was then conducted. Four different tests schedules or duty cycles were utilzied with each level of threshold pressure difference as follows:

1. Columbus city traffic schedule.
2. 25 snubs, 40-20 mph at 6 ft/sec^2, 45 sec interval.
3. 6 percent grade descent simulation - constant drag for 3 miles at 30 mph.
4. 4 percent grade descent simulation - constant drag for 5 miles at 45 mph.

Each of these schedules was repeated twice for each threshold pressure difference and the results of the tests were averaged.

The Columbus city traffic schedule, an actual on-road schedule, was run with the combination vehicle fully loaded (80,000 lb). The route utilized subjected the vehicle to high speed freeway driving as well as lower speed heavy traffic situations. This test was always run at the same time of day on weekdays so that variation in traffic density between runs would be minimal.

The other three test schedules were run with the fully loaded combination on the Transportation Research Center (TRC) 7.5 mile high speed track. The 25 snub (40-20 mph) schedule was an attempt to represent downhill braking using the snubbing technique (also representative of driving in city traffic). The 6 percent and 4 percent grade simulations were run to represent descending grades using the constant drag technique. Both techniques are used today by drivers when descending grades. These constant drag simulations were performed by towing the combination vehicle with a high powered tractor using a drawbar instrumented with a load cell. Figures 8 and 9 show the test set up. In these tests the driver of the towing tractor maintains a constant speed. The driver of the towed vehicle (i.e., the combination under test) uses his service brakes to maintain a constant drawbar force equivalent to the component of gravitational force that would be acting on the vehicle on an actual hill (i.e., percent slope times the weight of the vehicle).

Five different levels of threshold pressure difference between tractor drive and trailer brakes were evaluated in each of the tests. The first or reference level was that which was achieved with nominally the same relay valves on both sets of brakes. In this case, there was actually a slight threshold pressure difference of 0.3 psi with the trailer having the lower threshold pressure. For the other four levels, trailer relay valves with progressively higher crack open pressures were utilized to achieve progressively higher differentials in tractor and trailer thresholds. Threshold differences of 0.4 psi, 2.3 psi, 4.3 psi and 6.3 psi were achieved with the tractor having the lower threshold pressure in all cases.

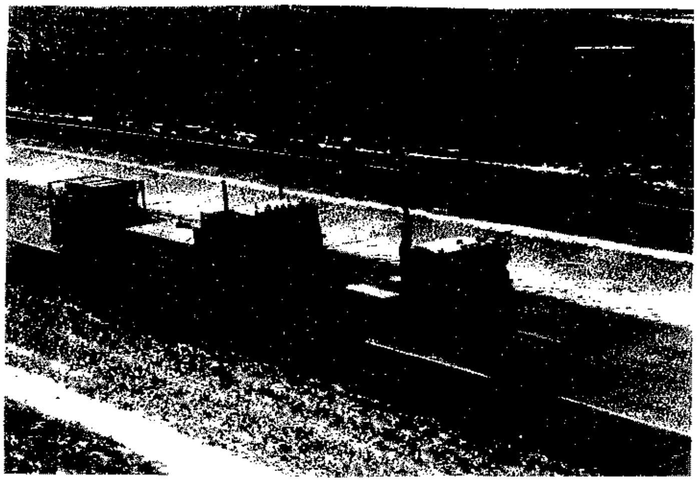

Fig. 8 - Tow tractor and combination vehicle used in grade descent simulations

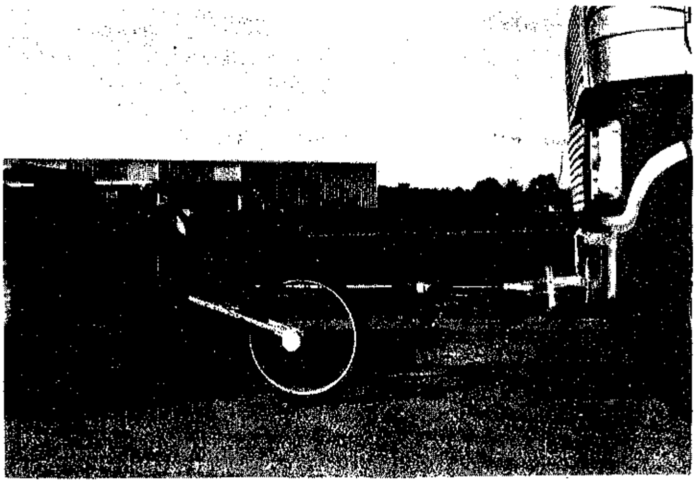

Fig. 9 - Instrumented draw bar used in grade descent simulations

Final brake lining temperature was utilized as the indicator of compatibility for the tests. Final tractor drive axle brake lining temperatures were averaged and compared to the average of the final trailer brake lining temperatures. Front (steering) axle brake temperatures, although measured, were not of particular interest since these brakes were much "smaller" and performed significantly less work. They typically ran at or below the temperature of the drive axle brakes during the tests. Threshold pressure of the steering axle brakes was approximately 0.5 psi higher than the drive axle brakes; an automatic pressure limiting valve was not used.

In order to evaluate the effect of brake lining conditioning during the tests, the reference level of threshold pressure differential (i.e., 0.3 psi trailer "leading") was reestablished after each trailer relay valve change and the four test schedules were repeated. These tests indicated that the relative level of tractor and trailer temperatures did not change significantly during the tests and that conditioning was not a significant factor to be considered in intrepreting the results.

Figures 10, 11, 12, and 13 give the results from the four test schedules. Figure 10 shows the Columbus city traffic results. With essentially zero difference in threshold pressure, the tractor drive axle brakes ran approximately 60°F hotter than the trailer brakes. This was probably due to the fact that the drive axle brakes were more effective. As threshold pressure differential increased this temperature difference increased. With the maximum threshold pressure differential evaluated (6.3 psi), the difference between tractor and trailer brake temperatures was approximately 230°F.

Figure 11 gives the results from the 25 snub test. Here again it can be seen that the tractor brakes ran hotter. In this case, however, the temperature difference was not as sensitive to threshold pressure difference. This is attributed to the higher control pressures used in these snubs (20-25 psi) compared to those used in the city traffic schedule; threshold pressure became less significant as the brake application pressure increased. Temperature differences ranged from approximately 100°F at zero threshold pressure differential to approximately 200°F at the 6.3 psi differential.

Figure 12 shows the results from the 6 percent grade simulation. Again the more effective tractor brakes ran hotter; but in this case the temperature difference increased significantly with increasing threshold pressure differential, reaching 350°F at the 6.3 psi threshold pressure differential. Again, the higher degree of sensitivity to threshold pressure is attributed to the relatively low control line pressures (7-12 psi) used in these constant drag tests.

Figure 13 shows the results of the 4 percent grade descent simulation. Here it can be seen that the tractor and trailer ran at essentially the same temperature when the threshold pressure difference was essentially zero. This is significant because it indicates that even if the

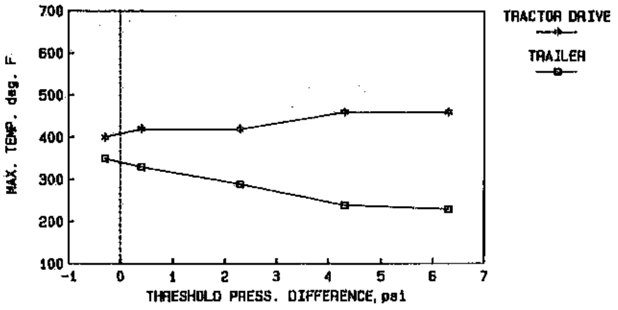

Fig. 10 - Brake temperatres in Columbus city traffic

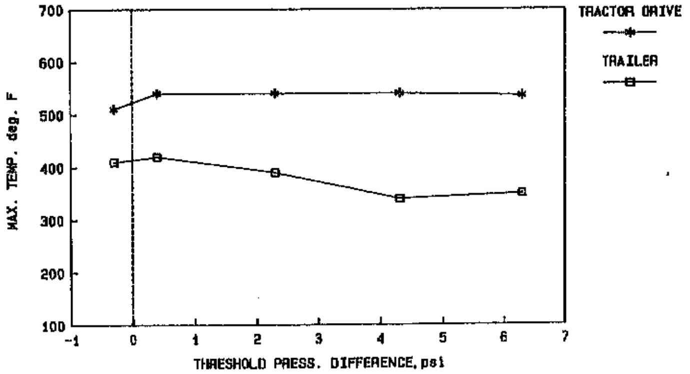

Fig. 11 - Brake temperatures for 25 snubs at 6 ft/sec^2, 45 sec interval

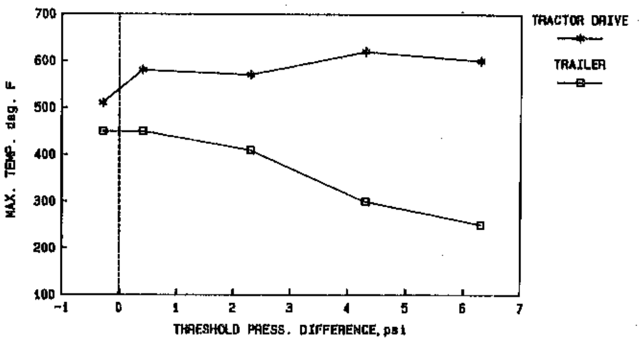

Fig. 12 - Brake temperatures for 6% grade simulation -- three miles at 30 mph

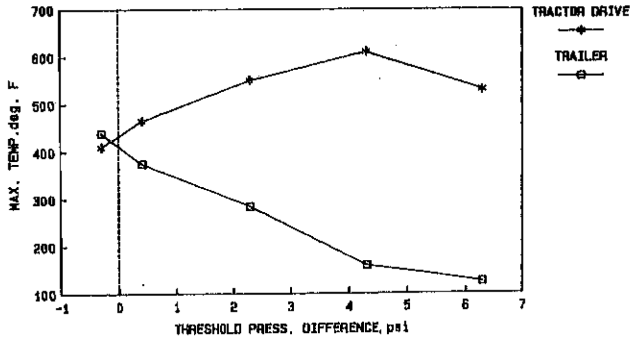

Fig. 13 - Brake temperatures for 4% grade simulation -- five miles at 45 mph

tractor is more effective than the trailer, which it was for this vehicle, matching threshold pressures will result in matched temperatures or essentially "good" compatibility during very low pressure brake applications. Sensitivity of temperature difference to threshold difference was dramatic in this test. With only a 2 psi difference in threshold pressures, the temperature difference was almost 250°F.

The results of this 4 percent grade test indicate that threshold pressure, and not brake effectiveness, established compatibility in very low pressure brake applications. Grades of 4 percent or less are relatively common on the nation's highways. Drivers typically must lightly drag the brakes to maintain vehicle speed on such grades. Although most brake drags do not last for 5 miles as in the test, every low pressure application with threshold pressure differences affects the brake work distribution and the cumulative effect on brake wear over many miles of driving can be significant.

Another significant finding from the threshold pressure differential tests is that making snubs to control speed on grades as opposed to applying a constant drag will minimize the effects of threshold pressure differentials and promote improved compatibility. This is because snubs use higher application pressures than constant drag applications. If the brake force versus chamber pressure is not balanced, however, brake temperature balance will still not be achieved even in the snub approach. Additional research is needed to study the snub versus constant drag approach before it can be concluded that one method is better than the other in general. There may be other factors that make the snub approach unsuitable.

With the results of the threshold pressure differential tests in mind, the significance of the threshold pressure data for the 15 vehicle sample (Table 3 and Figure 7) on compatibility can be assessed. From Table 3 it can be seen that differences in threshold pressures between the drive axles and trailer (and dolly) axles for the 15 vehicle combination sample varied from essentially zero to as high as 4.5 psi (combination vehicle 7). In addition, if the "high" tractor from combination 9 were coupled to the "low" trailer from combination 7, threshold pressure difference could go as high as 4.9 psi. Figures 10-13 (particularly Figure 13) indicate that such a threshold pressure difference could produce a large temperature difference between the tractor and trailer brakes and, thus, poor compatibility. The high front axle brake threshold pressures seen in Table 3 and Figure 7 indicate that front axles generally do less than their "fair share" of the braking in low pressure applications; in fact, in grade descents where the control line pressures are low, front axle brakes would never apply in many cases. This places more of the braking task on the tractor drive and trailer axles causing them to wear out and/or overheat faster.

The pressure differential measurements made on the 15 combination test vehicles indicate that most of the differences in threshold pressures between axles and vehicles were due to differences in relay, quick release or automatic front axle limiting valves. Most of the foundation brakes, all of which were cam type drum brakes, required similar pressures in the brake chambers at the brake force threshold. Usually 3-4 psi was required at the brake chamber to start brake force on apply and a reduction to 1-3 psi was necessary before the brake would release. In some cases front axle brakes required slightly higher pressures in the brake chambers for apply and release.

On combination vehicles that utilize cam type drum brakes exclusively, threshold relationships are primarily a function of valve characteristics. Those axles with high thresholds are those that utilize high crack pressure (input pressure to open) valves. The very high threshhold pressures found on the front axles in the 15 vehicle sample were caused by the use of automatic limiting valves with high crack pressures.

Balancing brake threshold pressures on cam braked vehicles, therefore, appears to be a function of pneumatic system design and the selection of appropriate valves. In those cases where different design brakes (wedge or disc) are mixed with cam brakes it is important that brake characteristics also be considered along with valve characteristics in the overall brake system design.

BRAKE FORCE DISTRIBUTION (STEADY STATE) - In the previous section it was shown that brake force thresholds (which in effect establish the starting points for the brake force versus control line pressure relationships that determine brake force distribution) affect brake temperature distribution. It was also shown that brake force distribution at higher pressures affects temperature distribution, particularly in situations where the brakes are repeatedly applied at pressures well above the threshold levels. Brake force distribution, therefore, impacts wear (or durability) and fade resistance since both of these are dependent upon brake temperature distribution.

Brake force distribution also has a significant effect on the maximum deceleration that a vehicle is capable of achieving before wheel lockup occurs. It is an important parameter to consider in assessing compatibility. As mentioned earlier, "nominal" design practice in the U.S. is to balance brake forces in accordance with GAWRs. The brake force distribution data obtained on the 15 combination vehicles were reviewed to determine how close they came to such a design target.

Table 4 gives the GAWR distribution and brake force distribution for the 15 test vehicle combinations. Brake force distribution shown was that determined at 40 psi, the highest pressure used in the J1505 procedure. This level was chosen for comparative purposes because it is well above the threshold level and represents approximately the middle of the actual operational pressure range on most vehicles. At pressures closer to the threshold levels, brake force distribution can change rapidly with pressure if threshold levels are significantly different. Distribution typically begins to reach a relatively constant level when pressure is increased to 40 psi. Above 40 psi, relatively small changes in distribution occur because of threshold pressure difference. The primary purpose of Table 4 is to identify vehicles that have brake force distributions significantly different than their GAWR distributions; these vehicles were studied in detail.

TABLE 4 -- GAWR Distribution and Brake Force Distribution at 40 psi

Combination		Distribution, Percent				
Vehicle		Front	Drive	Trailer 1	Dolly	Trailer 2
1	GAWR	15.2	43.0	41.8		
	Force	8.0	54.0	38.0		
2	GAWR	14.0	39.5	46.5		
	Force	10.1	51.7	38.3		
3	GAWR	13.7	38.9	47.4		
	Force	12.5	49.7	37.8		
4	GAWR	15.0	42.5	42.5		
	Force	7.4	42.9	49.6		
5	GAWR	14.0	39.5	46.5		
	Force	7.3	49.6	43.1		
6	GAWR	15.0	42.5	42.5		
	Force	4.5	46.8	48.7		
7	GAWR	15.0	42.5	42.5		
	Force	6.4	46.5	47.1		
8	GAWR	13.4	43.3	43.3		
	Force	5.5	32.5	62.0		
9	GAWR	14.0	39.5	42.5		
	Force	8.8	53.3	37.8		
10	GAWR	14.7	24.5	20.2	20.2	20.2
	Force	10.5	26.9	19.2	20.4	23.0
11	GAWR	12.7	23.5	22.0	19.7	22.0
	Force	11.5	18.5	26.4	18.5	25.1
12	GAWR	*	*	*	*	*
	Force	8.6	25.5	23.4	19.2	23.2
13	GAWR	12.0	22.3	22.3	21.2	22.3
	Force	8.1	17.4	28.4	19.1	27.1
14	GAWR	12.9	22.7	21.5	21.5	21.5
	Force	6.4	21.5	22.0	24.4	25.8
15	GAWR	13.0	21.7	21.7	21.7	21.7
	Force	7.0	29.2	22.4	22.2	19.3

*Not possible to calculate since GAWR of dolly was not recorded.

It can be seen from Table 4 that a number of the combination vehicles have brake force distributions that are different than their GAWR distributions. Vehicle 6, for example, has a relatively low percentage of braking on its front axle. Most of the vehicles are "underbraked" on their front axles due primarily to the use of automatic pressure limiting valves; but vehicle 6 has the least percentage of braking on the front axle. Vehicle 8 is the tractor semi-trailer and vehicle 13 is the doubles combination with the highest deviation from GAWR distribution at the trailer axles. Vehicle 9 is the tractor semi-trailer and vehicle 15 is the doubles combination with the greatest deviation at the drive axles. In order to show the effect of these deviations on braking performance, the braking efficiencies of vehicle combinations 6, 8, 9, 13 and 15 were calculated with the vehicles both empty and loaded. These braking efficiencies were compared to the efficiencies that would have existed had the brake force distributions been equivalent to the GAWR distributions.

Braking efficiency is a measure of a vehicle's ability to utilize available tire/road friction. It is defined as 100 times the ratio between the deceleration a vehicle can attain on a given surface without locking any wheels and the maximum possible deceleration without wheel lockup for that surface. The maximum possible (or ideal) deceleration is simply the deceleration due to parasitic drag plus the peak coefficient of friction of the surface times g (acceleration due to gravity). This ideal level is only possible when brake force distribution is equivalent to normal force distribution at the axles. It should be noted that balancing brakes such that brake force distribution is equivalent to GAWR distribution does not approximate ideal braking or 100 percent efficiency except for the case where the vehicle is loaded such that all axles are at GAWR and being braked on a wet ice surface (essentially zero deceleration). This is due to the fact that normal loads change due to inertial effects when non-zero decelerations exist. Also, when the vehicle is empty, weight distribution on the axles is usually significantly different than the GAWR distribution.

Braking efficiency corresponding to the actual measured brake force distribution was determined for combination vehicles 6, 8, 9, 13 and 15 as follows:

1. A linear brake force versus control line pressure relationship was established for axles on each vehicle using data obtained in the SAE J1505 tests and the least squares fitting technique, forcing the line through the threshold pressure, zero force point. This line was then extrapolated to 100 psi the maximum pressure that typically can be achieved on most vehicles (SAE J1505 only provides data to 40 psi which is insufficient to predict braking efficiency when the vehicle is loaded and operating on high coefficient of friction surfaces). A review of the J1505 data indicates that the linear assumption is reasonable. The exceptions to this

linear assumption were those front axles where automatic limiting valves were utilized. Such valves introduce a non-linear relationship since control line pressure is "modified" by the valve before reaching the brake chamber. For these cases, the measured pressure differential data was utilized to determine valve characteristics. Utilizing the valve characteristics and the front brake force versus <u>brake chamber</u> pressure relationship, which was assumed to be linear, the non-linear brake force versus <u>control line</u> pressure relationship was established.

2. Brake force versus control line pressure relationships for each axle established in step 1 were utilized to determine total brake force and corresponding vehicle deceleration for an input control line pressure of 2 psi. Vehicle parasitic drag deceleration (also determined in the SAE J1505 test) was added to this deceleration to obtain total vehicle deceleration during braking. This step was repeated in 2 psi control line pressure increments up to 100 psi with the vehicles empty and fully loaded. For the empty cases, axle weights measured when the vehicles were received were utilized. For the loaded cases, a "standardized" loading arrangement was utilized. Although loaded axle weights were available from the SAE J1505 tests, it was decided to use the standardized level for comparative purposes since loading is somewhat arbitrary. With the tractor semitrailers, a 12,000 lb (15 percent) front, 34,000 lb (42.5 percent) rear, and 34,000 lb (42.5 percent) trailer (80,000 lb total) loading was assumed since this is in accordance with Federal weight limits. For the fully loaded doubles, a 10,000 lb (12.5 percent) front, 17,500 lb (21.9 percet) drive, trailer 1, dolly and trailer 2 loading (also 80,000 lb total) was assumed. Since Federal limits allow up to 20,000 lb per single axle, the load distribution to arrive at the 80,000 lb total weight limit can be achieved with a wide variation of load distributions on doubles. The front axle loading of 10,000 lb is typical based on a review of the loaded test weights for the 6 doubles in the SAE J1505 tests. (Operators have relatively little control over front axle weights; they are primarily determined by tractor characteristics and do not change significantly with the trailer loading). Drive trailer 1, dolly and trailer 2 axle load levels were established by simply dividing the remaining 70,000 lb load equally among the axles.

It should be noted that the loaded weight distributions assumed do not necessarily correspond to GAWR distributions. This is not unusual since in many cases distributing loads in accordance with GAWRs will not allow a vehicle to reach 80,000 lb without exceeding the 34,000 lb tandem or 20,000 lb single axle Federal limits. In addition, the total of the GAWRs in many cases exceeds the 80,000 lb limit. Therefore, in actual practice, operators do not necessarily load in accordance with GAWRs. The specific impact of this phenomenon on braking efficiency will be addressed in more detail later.

3. Using equations written from free body diagrams of each vehicle in the combination, normal forces at each axle were calculated as a function of the total deceleration existing at each control line pressure input level. It was necessary to use vehicle dimensions measured at the time they were tested as input to these equations. Several required parameters not measured were assumed based on data available for similar vehicles; these assumed parameters included fifth wheel heights, dolly hitch and center of gravity (CG) heights. Since trailer loaded CG height depends on loading the assumption of this value was somewhat arbitrary; 66 inches was used for all trailers as this is the test CG height specified in FMVSS 121. Reference 1 includes free body diagrams and the equations necessary for calculating normal forces on a tractor semitrailer. Equations for a doubles combination are derived in a similar manner but are more complex algebriacally.

4. The ratio of the braking force (F) to the normal force (N) was then calculated for each axle at each control line pressure input level. The axle with the highest value of F/N would lock up first at a given input level and corresponding deceleration rate if the tire/road coefficient of friction was less than this maximum value of F/N.

5. Braking efficiency was calculated at each input level and is simply 100 times the total vehicle deceleration (d) existing at the input level divided by the coefficient of friction equivalent to the highest value of F/N existing among the axles.

$$\text{Braking Efficiency} = \frac{d}{F/N} \times 100 \qquad \text{Eq. (3)}$$

6. Braking efficiency was plotted at a function of tire/road coefficient of friction (F/N).

Braking efficiency versus tire/road coefficient of friction curves for the cases where the brake force distributions were equivalent to GAWR distributions were determined in a similar fashion except that in Step 1, linear brake force versus control pressure relationships with slopes in the same proportion as the GAWRs were assumed. Also, it was assumed that thresholds for each axle were identical. Front axles were assumed <u>not</u> to have limiting valves and, thus, their brake force was linear with respect to control line pressure.

Figures 14 through 18 show braking efficiencies as a function of tire/road coefficient of friction for vehicles 6, 8, 9, 13 and 15, respectively. In each figure, both the empty and fully loaded vehicle cases are shown. The solid lines in the figures represent efficiencies with "as-is" distributions (i.e., as determined by the SAE J1505 test results); the dotted lines represent the efficiencies that would exist if brake forces were distributed in the same ratios as the vehicle GAWRs and the threshold pressures were the same.

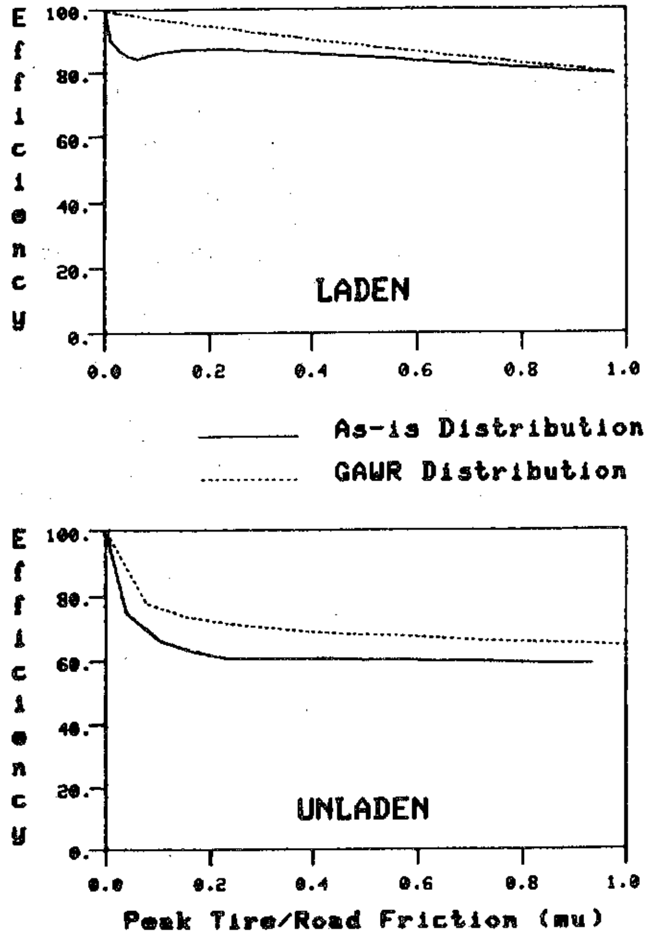

Fig. 14 - Braking efficiency for combination vehicle 6 (3-S2)

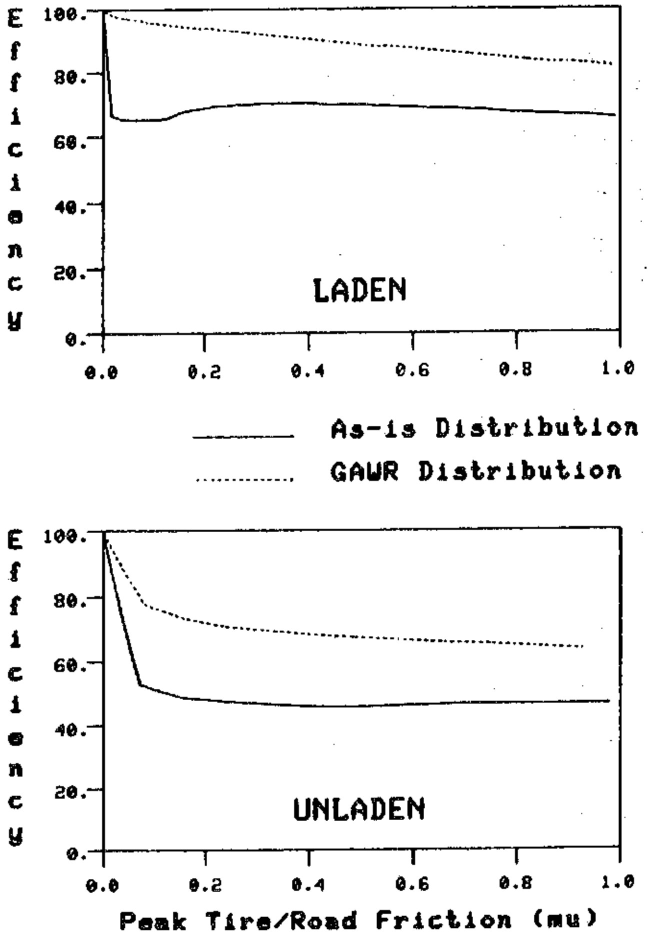

Fig. 15 - Braking efficiency for combination vehicle 8 (3-S2)

Figure 14 is for combination vehicle 6, the combination in Table 4 with the lowest percentage of braking on the front (steering) axle. Figure 14 indicates that the "as-is" distribution produced efficiencies lower than the GAWR distribution would have for both the empty and loaded cases. With the low level of braking on the steering axles, lockup of trailer axles or drive axles occurs at a low deceleration.

Figure 15 is for combination vehicle 8, the tractor-trailer in Table 4 with the highest level of trailer braking. It can be seen from Figure 15 that a GAWR distribution would have produced significantly higher braking efficiencies both empty and loaded. The high "as-is" trailer braking resulted in premature trailer wheel lockup.

Figure 16 is for combination vehicle 13, the doubles combination in Table 4, with the highest level of braking on the trailer axles. Again, the "as-is" distribution produced lower efficiencies, both empty and loaded, than those that would have occurred with a GAWR distribution. In this case, the efficiency curve calculations indicated that rear trailer wheel lockup limited performance with the "as-is" distribution. In a doubles combination, the rear trailer axle unloads more than the front trailer during braking and thus overbraking on this axle is more critical than overbraking on the front trailer axle.

Figure 17 is for combination vehicle 9, the tractor-trailer in Table 4, with the greatest percentage of braking on the drive axles. It can be seen that when the combination is loaded, the "as-is" distribution produces lower efficiencies than the GAWR distribution. When the combination is empty, however, the "as-is" distribution generally produces better efficiencies except on very low coefficient of friction surfaces (mu less than 0.13). One of the reasons that the "as-is" distribution produces lower efficiencies on low friction surfaces is the relatively low trailer threshold pressure (5.5 psi on trailer versus 8.8 on tractor drive) results in somewhat premature trailer wheel lockup. This drop in efficiency at low mu would not occur if the thresholds were equal.

Figure 17 indicates that for tractor-trailers there may be an advantage in having tractor drive axle braking somewhat higher (or the trailer lower) than the GAWR distribution dictates. Although loaded efficiency drops with a relatively high level of drive axle brake force (or low level of trailer brake force), the empty efficiency improves. Since it is the empty efficiency that is the poorer of the two loading cases, "worst case" efficiency of the vehicle

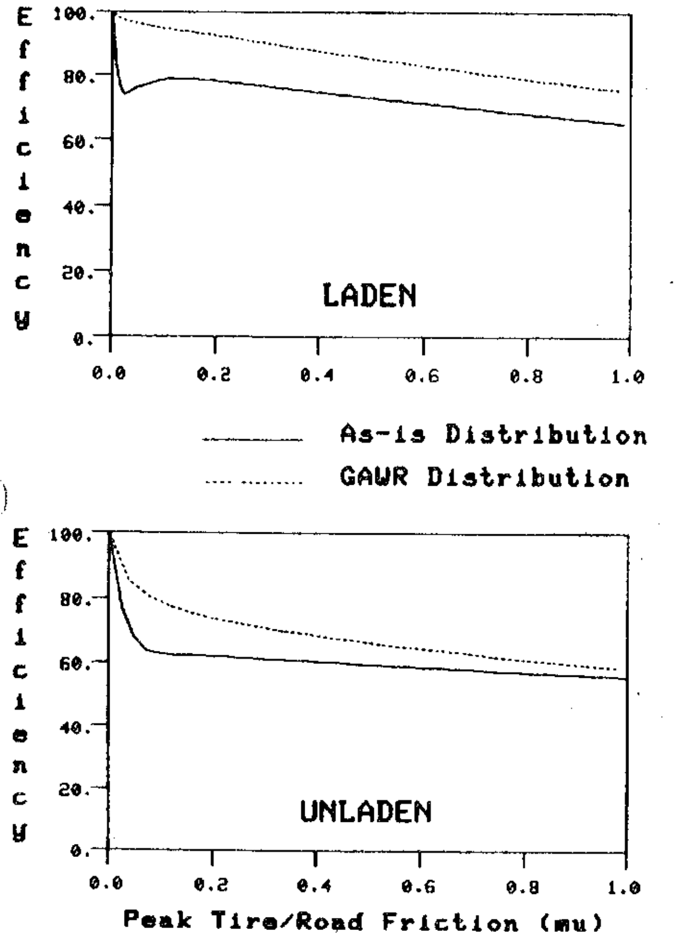

Fig. 16 - Braking efficiency for combination vehicle 13 (2-S1-2)

would be improved with such a distribution. Increasing drive axle brake force above the percentage dictated by GAWR will be discussed in more detail later.

Figure 18 shows efficiencies for combination vehicle 15, the doubles combination, with the greatest percentage of braking on the tractor drive axle. Figure 18 indicates that the "as-is" distribution produces significantly lower efficiencies with the loaded vehicle than the GAWR distribution. With the "as-is" distribution, premature drive axle lockup occurs loaded. With GAWR distribution, rear trailer lockup limits efficiency but the efficiency is significantly higher. With the empty doubles combination, both distributions produce essentially the same efficiency although the GAWR distribution provids slightly higher efficiencies on very low coefficient of friction surfaces.

In summary, Figures 14-18 indicate that vehicles with GAWR distributions and equal threshold pressures would have produced higher braking efficiencies than those with significant deviations from the GAWR distributions and differences in threshold pressures. The only exception was the case of the empty tractor semitrailer (vehicle 9) where an increase in tractor drive axle braking above (or decrease in trailer braking below) the level corresponding to

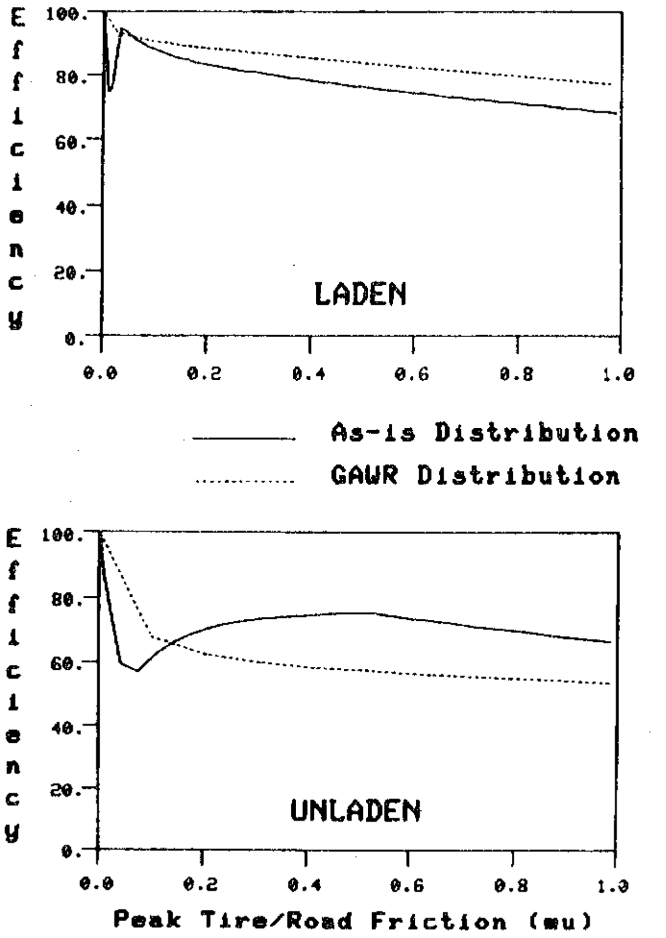

Fig. 17 - Braking efficiency for combination vehicle 9 (3-S2)

the GAWR distribution produced an improvement in efficiency. On this combination, however, loaded efficiency was lower with the "as-is" distribution than the GAWR distribution.

To study this phenomenon further, another tractor semitrailer combination (vehicle 6) was evaluated over a range of distributions to determine what distribution would have produced optimum efficiency. This evaluation was performed as follows: A reference level of efficiency was established by first assuming GAWR distribution and equal thresholds. Without changing thresholds, trailer braking was then decreased (placing a higher percentage of the braking on the tractor) in increments until empty efficiency peaked. Corresponding loaded efficiencies were also calculated. As the trailer braking was decreased, the corresponding increase on the tractor was distributed onto the tractor axles in the ratio corresponding to the tractor GAWRs (i.e., 12:34). In effect, this produced an increase in the percentage of braking at <u>both</u> the front and drive axles above the GAWR percentages.

Figure 19 gives the efficiencies for the reference GAWR distribution (15 percent front/42.5 percent drive/42.5 percent trailer) and the "optimum" distribution (16.3 percent front/46.1 percent drive/37.7 percent trailer). It can be seen from this figure that empty efficiency is

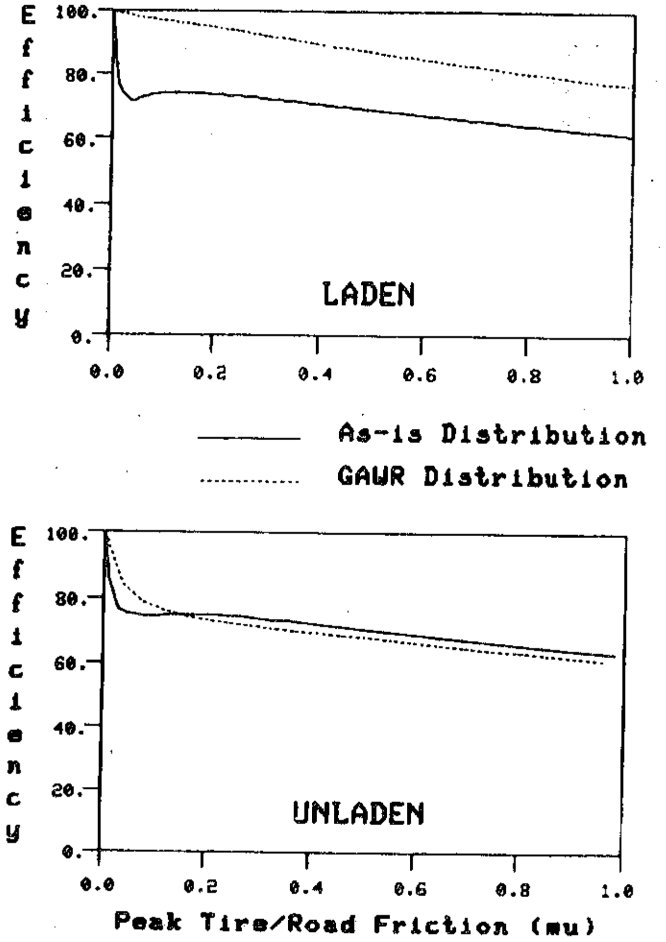

Fig. 18 - Braking efficiency for combination vehicle 15 (2-S1-2)

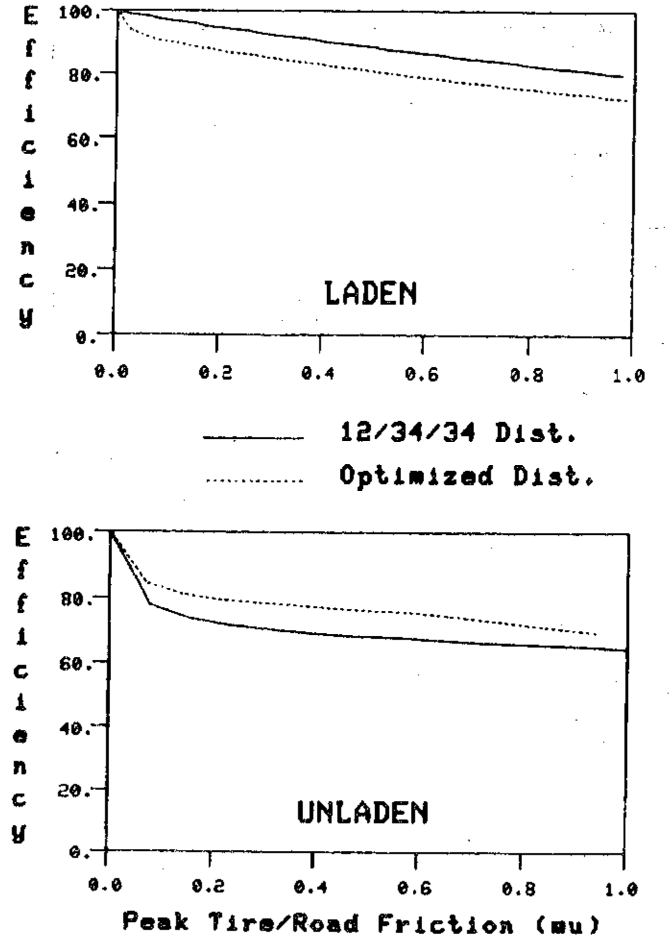

Fig. 19 - Braking efficiency for combination vehicle 6 (3-S2) with GAWR and "optimized" brake force distributions

improved but loaded efficiency drops with the reduced trailer/increased tractor braking. Since the empty efficiency is the lower of the two loading cases, the minimum efficiency of the vehicle is raised with this "optimum" distribution. One draw back to this reduction in trailer braking and (increase in tractor braking) is the fact that tractor brakes would be doing more work in sublimit, "everyday" braking situations. This could result in premature wear out or possibly overheating of tractor drive axle brakes unless appropriate adjustments are made in the brake system design to balance temperatures and wear rates.

Before recommending that brake force distributions on tractor semitrailers should be different than GAWR distributions (i.e., more tractor braking/less trailer braking), more research would be needed to determine the overall impact on vehicle durability and safety. Although empty braking efficiency (which is lower than loaded braking efficiency) could be improved, there might be negative safety impacts related to the reduction in loaded efficiency that occurs with such "non-GAWR" distributions. In addition, depending upon vehicle weights and dimensional parameters, an increase in braking at the tractor drive axles can result in lockup of the drive axles well before the trailer axles. Since the tendency for a vehicle to jackknife (caused by drive axle lockup) is more difficult for a driver to control than trailer swing (caused by trailer wheel lockup), maintaining trailer swing as a limit condition may be desirable.

It was maintained earlier that GAWR distribution on a vehicle may not necessarily correspond to fully loaded vehicle axle weight distribution. To study the impact that this has on braking efficiency, the braking efficiency of combination vehicle 9, where such a phenomenon exists, was evaluated in more detail. Vehicle 9 has GAWRs of 12,000 lb front, 34,000 lb rear, 40,000 lb trailer yet due to Federal weight limits, would usually only be loaded to 12,000 lb front, 34,000 lb rear and 34,000 lb trailer (80,000 lb total). Figure 20 shows braking efficiencies for vehicle 9 with two different brake force distributions: 12:34:34 corresponding to fully loaded weight distribution) and 12:34:40 (corresponding to GAWRs). Threshold pressures were assumed to be equal at all axles in both cases. It can be seen from Figure 20 that the brake force distribution corresponding to the fully loaded weight distribution produces higher braking efficiencies both empty and

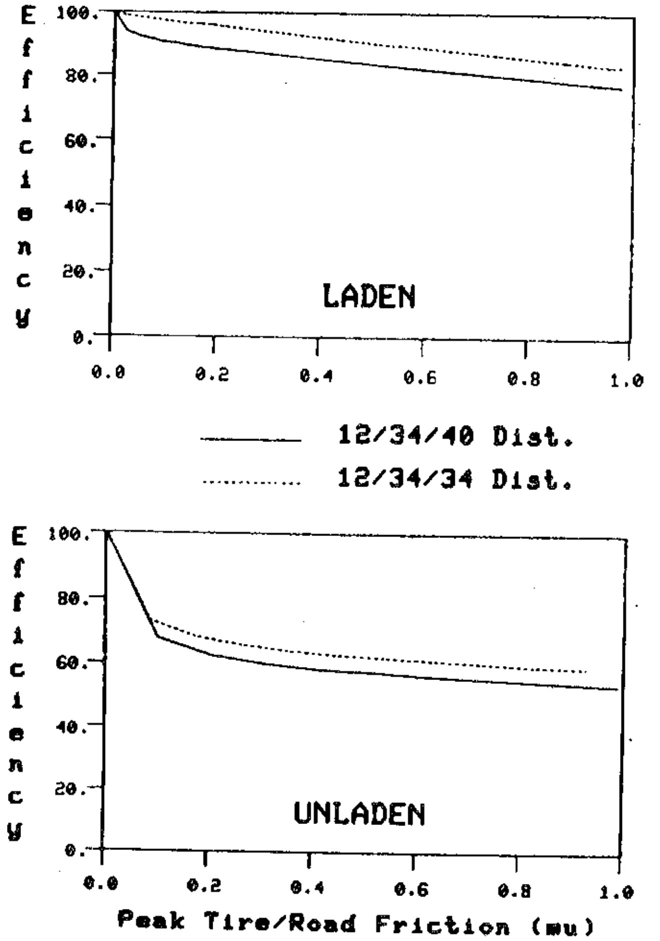

Fig. 20 - Braking efficiency for combination vehicle 9 (3-S2) with brake force distributions equal to GAWR and fully loaded vehicle weight distributions

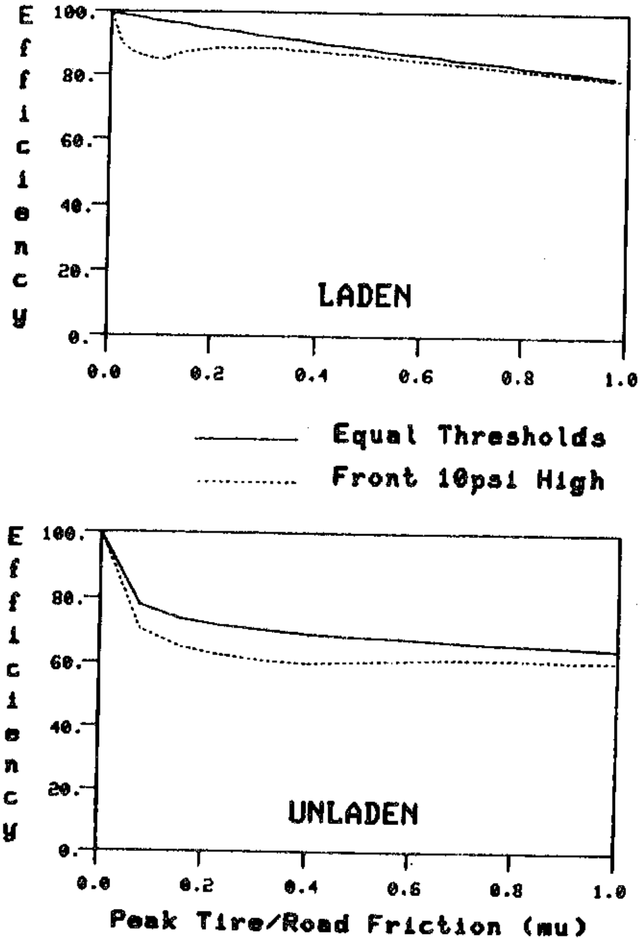

Fig. 21 - Braking efficiency for combination vehicle 6 (3-S2) with equal threshold pressures and 10 psi "high" front threshold distributions

loaded. With the 12:34:40 distribution the trailer simply has too much braking and trailer wheel lockup occurs at lower decelerations.

It would appear from this analysis that when purchasing vehicles, specifications of brake force distribution that correspond to maximum loaded vehicle weights is desirable. Many vehicle purchasers specify high GAWRs primarily to obtain heavy duty axles that have greater durability. Unfortunately, when this happens, the brakes on these axles are larger than needed since they must meet FMVSS 121 requirements which are based on the GAWR. A better approach would be to specify GAWRs that correspond to expected fully loaded vehicle weights and then in addition, specify higher heavy duty axles (i.e., axles that are rated above the GAWR level). In this way more durable axles can be obtained along with more appropriate brake force distributions.

Using the above calculation approach it is also possible to determine the effect of threshold pressures on braking efficiency. Weights and dimensions from combination vehicle 6, a typical tractor semitrailer, were utilized in this analysis. A GAWR brake force distribution was assumed (i.e., 12:34:34). Figure 21 shows the effect of a high front axle threshold pressure. For this case, it was assumed that the front axle has a threshold pressure that is 10 psi above the thresholds of the trailer and drive axles (assumed to be equal). High steering axle threshold pressures are not unusual. Figure 7 shows the thresholds for the 15 combination vehicles to range from 4.5 to 15.0 psi. Thresholds for trailer and drive axles on the other hand varied from only 3.3 to 8.8 psi. A 10 psi difference at the front axle would, therefore, not be unreasonable. It can be seen from Figure 21 that when compared to the reference case of equal thresholds, a 10 psi difference at the front axle produces lower braking efficiencies for both the empty and loaded cases, particularly on low coefficient of friction surfaces. The calculations indicate that when the vehicle is loaded, drive axle lockup occurs first and is more premature with the higher front axle threshold. In the empty case, trailer axle lockup occurs first and is more premature.

Figure 22 shows the effect of a low trailer brake force threshold pressure. In this case, it was assumed that the trailer brakes applied at a pressure 4 psi lower than did the tractor drive and steering axles. A review of the data in Table 3 indicates that for the nine tractor

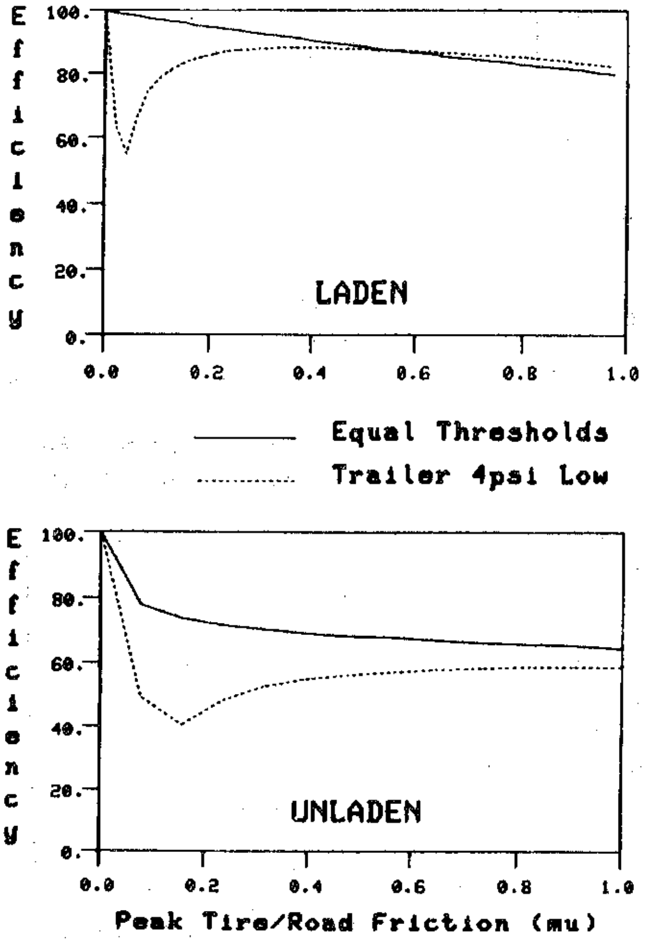

Fig. 22 - Braking efficiency for combination vehicle 6 (3-S2) with equal threshold pressures and 4 psi "low" trailer threshold

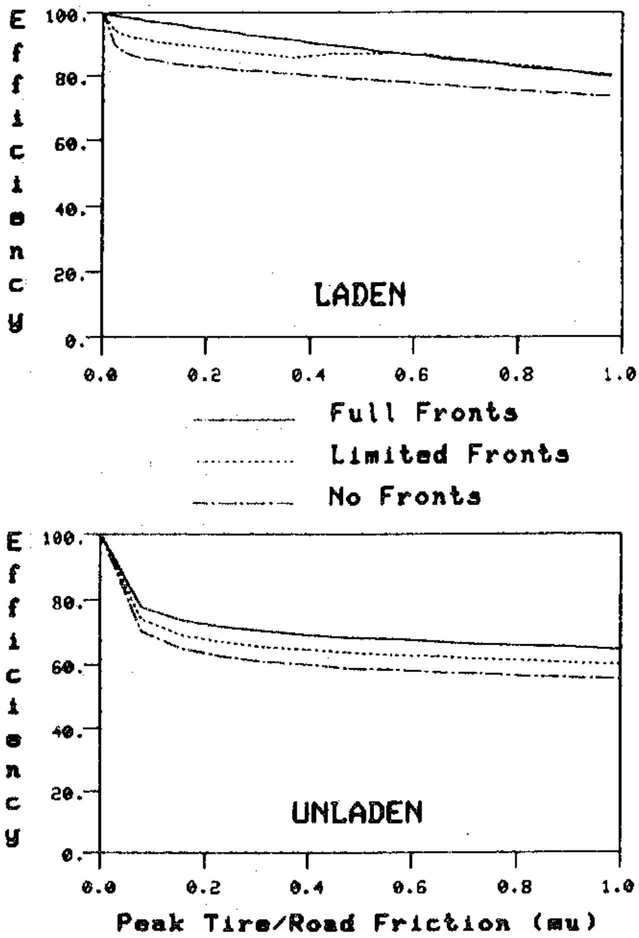

Fig. 23 - Braking efficiency for combination vehicle 6 (3-S2) with three levels of front axle braking

semitrailers, trailer thresholds were typically lower than tractor thresholds. Vehicle 7, in fact, had a trailer threshold pressure that was 4.5 psi below the tractor drives and 5.9 psi below the tractor fronts. It can be seen from Figure 22 that the effect of this low trailer threshold is dramatic, particularly in the empty case. Trailer wheel lockup (which also occurs before tractor drive wheel lockup even with equal thresholds) becomes very premature when empty, especially on low mu surfaces if the trailer threshold is low. In the loaded case, the calculations show that the "limiting" axle changed from the tractor drive when thresholds were all equal to the trailer when the trailer threshold was 4 psi low. Premature trailer wheel lockup is very pronounced on very low coefficient of friction surfaces such as ice when the vehicle is loaded.

It is also possible using the braking efficiency calculation approach to study the effect of front brake effectiveness on performance. Figure 23 shows the effect of different levels of front braking on braking efficiency of a tractor semitrailer. The weights and dimensions of combination vehicle 6 were utilized and the brake force distribution was assumed to be equal to GAWR distribution (12:34:34). Equal threshold pressures were also assumed for all axles. Three different levels of front braking are shown: 1) Full fronts (i.e., corresponding to GAWR distribution), 2) limited fronts (i.e., full front brakes but with a typical automatic limiting valve installed), and 3) no front brakes. The characteristics of a typical limiting valve were determined by reviewing the pressure differential data available from the 15 vehicles (11 had front axle limiting valves).

Figure 23 shows that the best braking efficiency for the empty and loaded conditions occurs with full front brakes and the poorest efficiency with no front brakes. Limited front brakes produced efficiencies somewhere in-between. When the vehicle is loaded and on high coefficient of friction surfaces, efficiency with limited front brakes and full front brakes is essentially equal. This is due to the "blend back" feature of the typical automatic limiting valve. Between 40 and 60 psi the valve gradually changes from 50 percent pressure reduction to no pressure reduction. Above 60 psi the valve does not limit pressure. This blend back region can be seen on the loaded curve in Figure 23. With the empty vehicle, the pressures needed are below the blend back feature of the valve even on high coefficient of friction surfaces.

The effect of front brake limiting valves on efficiency was further studied by analyzing vehicle 10, a doubles combination. This vehicle is of particular interest because it utilizes front brakes that are unusually "large". Vehicle 10 was equipped with 16-1/2 x 5 inch cam type drum brakes with 5.5 inch slack adjusters and type 20 chambers. All of the other 14 combinations utilized either 15 x 4 or 15 x 3-1/2 inch brakes with 5.5 inch slack adjusters and type 12, 16 or 20 chambers. The J1505 test data shows vehicle 10 to have front brake forces that are higher (for a given front brake chamber pressure) than those of any other vehicle.

Figure 24 shows the braking efficiencies of vehicle 10 both with and without its front brake limiting valve. With the valve, the "as-is" distribution (determined in the J1505 tests) was utilized along with valve characteristics (determined by the pneumatic system pressure differential tests) to extrapolate the brake force distribution from 40 psi to 100 psi. Efficiency without the valve was determined by simply removing the effect of the valve in the calculations.

Figure 24 indicates that for both the empty and loaded cases, removal of the valve improves efficiency. At both loads, with or without the valve, drive axle lockup limits performance; however with the valve this drive axle lockup occurs at lower decelerations. It does not appear that use of the valve is desirable on this vehicle even though it has a high level of front brake force. There may be benefits to using automatic limiting valves with front brake forces greater than those evaluated here but such braking forces are not representative of current U.S. vehicles.

The effects of front axle brake force level on vehicle braking efficiency indicated in Figures 23 and 24 are in agreement with full scale vehicle test data that are available. Reference 1 describes tests that were run on a number of vehicles with and without front brakes and with and without automatic front brake limiting valves. Straight line stops as well as stops in a curve and lane change were performed on a range of surfaces from ice to dry pavement. In all cases, these vehicle tests indicated that the shortest controlled stopping distance was achieved with full front brakes. Removal of the limiting valve always produced better brake system performance in these maneuvers.

In addition to their effect on braking efficiency and limit braking performance, recent tests conducted by the VRTC also indicate that front axle limiting valves have a measurable effect on brake work balance in sublimit braking situations. By limiting the work done by the front axle brakes, front axle limiting valves cause more work to be done by the tractor drive and trailer axle brakes in a given braking situation. This results in higher drive and trailer axle brake temperatures as seen in Table 5 which shows the results of 4 percent and 6 percent grade simulations for a fully loaded (80,000 lb) five axle tractor-trailer combination with and without a front brake limiting valve. The temperatures shown in Table 5 are those measured in the brake linings and represent average values for the two brakes on the front

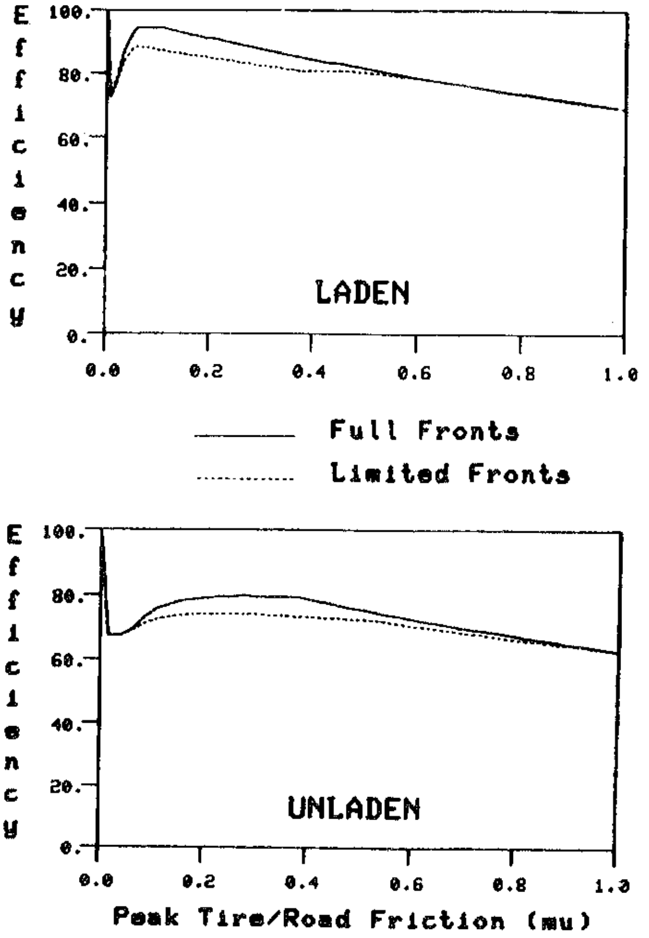

Fig. 24 - Braking efficiency for combination vehicle 10 (2-S1-2) with and without automatic front brake limiting valve

TABLE 5 - Final Brake Temperatures (°F) for a Loaded Tractor Semitrailer With and Without a Front Brake Limiting Valve

	4% Grade -- 5 Miles at 45 mph			6% Grade -- 3 Miles at 30 mph		
Front Brakes	Front	Drive	Trailer	Front	Drive	Trailer
With Limiting	108	483	361	216	567	399
Without Limiting	496	432	304	451	528	386

8. ECE Regulation No. 13, "Uniform provisions concerning the approval of vehicles with regard to braking," Published by the United Nations in Geneva (E/ECE/TRANS/505 - Rev. 1/Add. 12/Rev. 2/Amend. 2, dated 15 February 1985).

9. EEC Directive 71/320, "On the approximation of the laws of the Member States relating to the braking devices of certain categories of motor vehicles and of their trailers," Council Directive of 26 July 1971, published in the Official Journal of the European Communities No. 202, 6.9.71.

10. Heavy Duty Trucking, "Fast But Legal," and "Solving a Brake Problem," pp. 48-56, July 1986.

11. Radlinski, R.W., Williams, S.F. and Machey, J.M., "The Importance of Maintaining Air Brake Adjustment," Society of Automotive Engineers, Paper Number 821263, November 1982.

12. "Brake Force Distribution Test Code-Commercial Vehicles -- SAE J1505," SAE Recommended Practice, May 1985.

13. "Vehicle Inspection Handbook -- Truck/Bus/School Bus," Prepared by Technical Affairs Division, Motor Vehicle Manufacturers Association of the United States, Inc., ISBN 0-943350-10-7, 1985 Revision.

14. Hargadine, E.O. and Klein, T.M., "Brake Performance Levels of Trucks: 1983," Engineering Economics Systems Group, Final Report, Contract Number DTFH61-83-C-00082, September 1984.

(Addendum to Paper)

Threshold Pressure Versus Braking Efficiency

In SAE Paper 861942, "Tractor and Trailer Brake System Compatibility," the effect of threshold pressure difference between tractor and trailer on vehicle braking efficiency was addressed. Figure 22 in the paper is shown here for reference purposes.

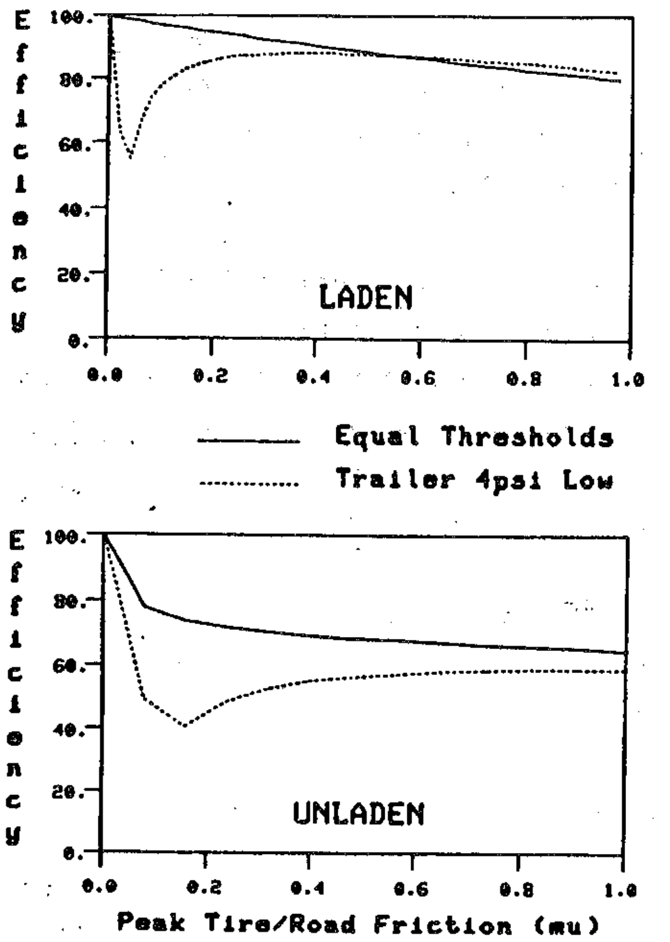

Fig. 22 - Braking efficiency for combination vehicle 6 (3-S2) with equal threshold pressures and 4 psi "low" trailer threshold

This figure, based on a computer simulation, shows that a 4 psi difference in threshold pressure has a dramatic effect on braking efficiency. If the trailer comes on "first" (i.e., 4 psi "before" the tractor) the trailer will lock up prematurely particularly when the vehicle is empty and on a low mu surface. Several weeks ago VRTC was able to conduct full scale vehicle tests in an attempt to verify this relationship. A "stock" tractor and trailer (being used for ABS testing) was available. This combination had a significant threshold pressure difference. The tractor utilized a nominal 8 psi crack pressure relay valve and the trailer relay valve had a nominal 4 psi crack pressure.

Threshold pressure measurements in accordance with J1505 indicated the following:

	Threshold, psi	
Tractor Front axle	7.0	
Tractor Drive Axles	9.2	Δ = 5 psi
Trailer Axles	4.2	

Tests were then run on this combination (w/o ABS) to determine stopping performance on a Jennite curve and in a Jennite lane change with the vehicle both empty and fully loaded. After these tests were completed, the tractor was modified so that its relay valve was nominally the same as the trailer relay valve (i.e., both with 4 psi crack pressure). A repeat of the threshold measurements showed the following:

	Threshold, psi	
Tractor Front axle	7.0	
Tractor Drive Axles	5.7	Δ = 1.5 psi
Trailer Axles	4.2	

The curve and lane change were then repeated. Test results for the road test are shown in the following table:

Table 1 -- Stable Stopping Distance
for two Levels of Threshold Difference

			Best Stop in Lane, ft		
mph	Maneuver*	Load	OE (Δ=5.0 psi)	Modified (Δ=1.5 psi)	Δ
35	Curve	Empty	422	310	112′
35	Lane Change	Empty	435	294	141′
35	Curve	GVWR	251	233	18′
35	Lane Change	GVWR	238	229	9′

*Tests run on wet Jennite (peak mu ≈ 0.3 with truck tire);
10 repeats at each condition.

It can be seen from Table 1 that with the threshold difference reduced to 1.5 psi (from 5 psi in the OE configuration), stable stopping distance empty dropped by over 100′ in both maneuvers. There was only a slight improvement with the lower threshold difference, however, when the vehicle was loaded.

Referring to Figure 22 from the SAE paper, this is essentially what the simulation would have predicted. If we assume a peak mu on the surface of 0.3, unladen efficiency should increase by 30% and laden efficiency should increase by 5% when the threshold difference is reduced from 4.0 psi to zero. (In our actual road test, Δ threshold was changed from 5.0 psi to 1.5 psi, a reduction of 3.5 psi.)

In addition to the test track stopping tests to evaluate braking efficiency, this vehicle (both "stock" and modified) was run fully loaded through the city of Columbus, Ohio. Three runs were made with the OE valves (Δ threshold=5.0 psi) and three runs were made with the reduced crack pressure drive axle valve (Δ threshold=1.5 psi). As was the case in previous tests, reducing the threshold differential reduced the tractor to trailer temperature differential. In this case, the differential between drive axle and trailer temperatures was reduced by 53°F on the average with the lower threshold differential.

Conclusion

The safe braking performance of combination vehicles is greatly impacted by the relationship between the threshold pressures on the tractor and trailer. Reducing the differential in thresholds between the two vehicles: 1) improves temperature balance and 2) maximum braking efficiency. Both of these improvements have now been clearly demonstrated in full scale vehicle tests.

Printed in U.S.A.