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16. Abstract

"A Braking Efficiency Test Technique" provides a method whereby vehicle stopping performance can be specified, measured, and compared independently of the test surface. The method provides for an independent measure of the prevailing friction potential of the test surface. This measure is used to normalize the measured stopping performance of the test vehicle. The concept presented is tailored toward a safety argument and toward rulemaking as a potential adaptation to braking effectiveness requirements which currently exist. A new mobile tire dynamometer, developed for this program, is discussed, as are the results of a demonstration test program carried out at the Bendix Automotive Development Center.

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1.0 INTRODUCTION

This document constitutes the summary final report on U.S. Department of Transportation Contract Number DOT-HS-031-3-765 entitled "Braking Efficiency Test Technique." This research study has been conducted by the Highway Safety Research Institute (HSRI) of The University of Michigan at its facilities in Ann Arbor, Michigan, with certain test activities being conducted at the facilities of the Bendix Automotive Development Center in New Carlisle, Indiana.

The program's primary objective has been the development of a method whereby vehicle stopping performance can be specified, measured, and compared independently of the test surface. The "independence" quality of the method derives from a technique by which a measure of the prevailing frictional "potential" of the test surface is used to normalize a vehicle's stopping performance, as measured on that surface. The normalized characterization thus quantifies the "efficiency" with which the vehicle is capable of utilizing the frictional limitations of the test surface to maximize deceleration. The measure which has been defined, however, involves a specialized concept of "efficiency" which derives from certain convictions concerning the safety relevance of vehicle limit braking capability. Whereas this concept is decidedly removed from "classical" braking efficiency as has been defined by J. A. Rouse (1) and others, the summary report begins with a discussion of the rationale which forms the conceptual basis for the study. It should be noted that the concept presented here is tailored not only toward a safety argument, but also toward rulemaking as a potential adaptation to braking effectiveness requirements which currently exist within FMVSS 105-75 and 121.

The concept, which has been developed into a test technique, is comprised of three basic elements which are discussed briefly here in the context of the developmental effort of this program. The technique is defined as requiring two physical measurement activities; one which addresses pavement friction, or more specifically, longitudinal traction potential, and the other which addresses vehicle limit stopping capability. The third element of the method, then, specifies a normalizing formula by which the braking efficiency numeric is computed.

Within this study a demonstration of the developed methodology has been achieved through the conduct of full-scale testing and the accompanying computations of the braking efficiency measure. The braking efficiency tests involved measurement of the limit braking performance of both a passenger car and a heavy truck, as well as the extensive application of a mobile dynamometer for measurement of surface friction. The mobile device, a major development of this study, is especially configured for measurement of the peak traction capability of a reference tire at varying load and velocity conditions.

Later in this report, the potential application of the developed braking efficiency test technique to rulemaking is examined, together with certain considerations which we feel to be natural outgrowths of the basic concept. A set of conclusions and recommendations is presented in summary of the program's findings as well as its implications for future research.

2.0 CONCEPTUAL BASIS FOR THE STUDY

Since the technique which has been developed in this study departs markedly from the classical definition of braking efficiency, it is appropriate that the underlying rationale be carefully articulated. The following discourse serves to establish certain positions upon which the rationale is founded, and to describe the measurement concept which has been pursued.

The major challenge of the study was to determine a method by which a measure of braking performance would obtain which has safety-meaning regardless of the surface employed. Accordingly, the question is raised "What influence does the surface have on determining the stopping distance which can be accrued?" The paved surface comprises only one component of the friction couple which sustains shear force at the tire-road interface. Since the role played by the pavement cannot, within current technology, be distinguished from the role played by the tire, it is not categorically feasible to characterize a pavement's friction force capability as an inherent property residing within the texture and chemistry of the pavement itself. Further, a given tire will generate shear forces on a given surface not only as related to the sum of the mechanical and chemical descriptions of both tire and pavement, but also as influenced markedly by the prevailing velocity and vertical load at which the tire is operated. Differences in surface texture, chemistry and contamination can cause changes in the relative influence of velocity and tire load on shear force capability.

As a consequence of these facts, the ASTM skid number measure was judged to be an insufficiently comprehensive characterization of the friction-related properties of a pavement. Whereas the ASTM method utilizes a single vertical load and single test velocity in deriving its measure, no mechanism exists to account for the influence of load and velocity as may be peculiar to the surface being measured. To the extent that the ASTM method represents the only recognized full-scale road friction standard, its shortcomings required that the subject braking efficiency method look to the development of a new tire-road friction measurement.

In determining a position to be taken concerning the tire-road friction characterization which is needed to effect a meaningful normalization of stopping distance, certain implications of a classical version of braking efficiency were addressed.

Classical braking efficiency can be defined as a measure of the extent to which a vehicle is capable of accruing the peak longitudinal force capability of each of its installed tires throughout the stopping process.

A number of characterizations which are basic to the classical braking efficiency concept render it unusable in a safety standards context. Firstly, it is clear that any derived classical braking efficiency measure provides no indication of absolute stopping performance capability. A vehicle could score a very high value of classical braking efficiency by effecting the high utilization of a traction-poor tire. Thus, since good stopping distance capability is not assured through the indication of a high value of classic braking efficiency, it is clear that a tire traction rule would be a necessary adjunct to any classical braking efficiency rule or specification. Further, since tire loading can seriously compromise the accrual of a tire's innate traction capability, it follows that a tire load rating rule would be needed as well.

In light of these and other observations, it was concluded that classical braking efficiency is unusable as a standard method by which stopping performance can be normalized. Instead, the subject study has pursued the development of a simplified normalization which derives its meaning and validity from a scenario of the safety implications of vehicles distributed serially in traffic streams.

It can be argued, in developing this scenario, that highway travel does not, by its very nature, impose any truly general requirement for the absolute braking performance of vehicles, although in each pure braking application there is some absolute performance requirement to be met if a collision is to be avoided. Accordingly, one can assert that more braking capability is better and, indeed, high levels of capability are probably desirable, but it cannot be claimed that a certain minimum level is essential.

On the other hand, the leading/following distribution of vehicles on the highway does impose an inherently meaningful requirement for relative braking performance. By this prospect, the relative braking capability of serially adjacent vehicles achieves safety meaning due to the likelihood of rear-end collisions as well as the disturbances in traffic flow which arise from the evasive tactics of the less capable braking performers in the stream.

A braking efficiency measure based upon relative performance departs from classical braking efficiency in that it normalizes a vehicle's stopping performance to account for the extent to which other vehicle/tire systems can utilize the available pavement-limited friction. (Rather than accounting for the frictional potential of the subject vehicle's own tires on the subject surface.) In the development of a standardized technique which involves adjustment for "other vehicle" characteristics, it becomes necessary to standardize the "other vehicle" representation. Thus we have defined a braking efficiency characterization which normalizes the stopping distance capability of vehicles against the reference stopping distance capability of "the mean passenger vehicle."

The NHTSA has espoused a comparable rationale in rule-making which requires a dramatic upgrading of the braking capability of commercial vehicles. Implicit in such rulings has been the notion that the mean passenger vehicle represents the norm, or reference, in stopping capability such that it is deemed wiser to upgrade commercial vehicle performance toward passenger vehicles rather than to downgrade passenger car performance. The fact that passenger cars comprise the majority of the vehicle population, and that they generally have exhibited the superior limit braking capability gives basis to the judgment that they represent a de facto norm for braking performance in the traffic system.

In terms of the braking efficiency measurement itself, the concept suggests that two concurrent stopping distance measures will be made on a given surface, using both the subject vehicle and the reference passenger vehicle. Because of concerns over the long-term repeatability of an actual passenger vehicle's performance, however, it was judged more practical to compute the stopping distance capability of the reference vehicle using tire shear force data which will have been gathered on the subject surface using a special test device. The tire defined to be installed on the hypothetical reference vehicle is one which exhibits a traction performance which is representative of the mean vehicle in the passenger car population.

The exercise of the method outlined here, and developed in the course of this study, yields a numeric characterization which is novel, but one which is proposed as being specifically addressed to a generally meaningful safety argument.

3.0 THE ELEMENTS OF A BRAKING EFFICIENCY TEST TECHNIQUE

Given the definition of a braking efficiency concept which centers around a reference vehicle scheme for normalization, the bulk of the study was concerned with development of the reference vehicle's performance characterization. Since at the outset we asserted the judgment that no physical vehicle could be used for a reference braking performance measurement, it became necessary to define a computation by which "reference" performance could be derived. The associated computation required the identification of a set of relevant vehicle parameters as well as a mathematical solution to the reference stopping distance expression.

The selection of basic inertial and geometric parameters was complemented by an effort to identify a truly representative reference tire. The reference performance computation would then include a set of parameters describing the traction capability of this tire, as it would be found to operate on the subject test surface. The traction measurements clearly required the development of a new test device—a major task in the program.

3.1 PARAMETERS OF THE REFERENCE VEHICLE

The geometric parameters describing the reference passenger vehicle are shown in Figure 1. Values for W, 1, and a were determined as representing the mean passenger vehicle in the U.S. on the basis of a compilation of available vehicle registration and parameter data. The c.g. height designation, h, was evaluated on the basis of limited laboratory measurements as representing a value which was compatible with the basic vehicle description already established by the other three parameters.

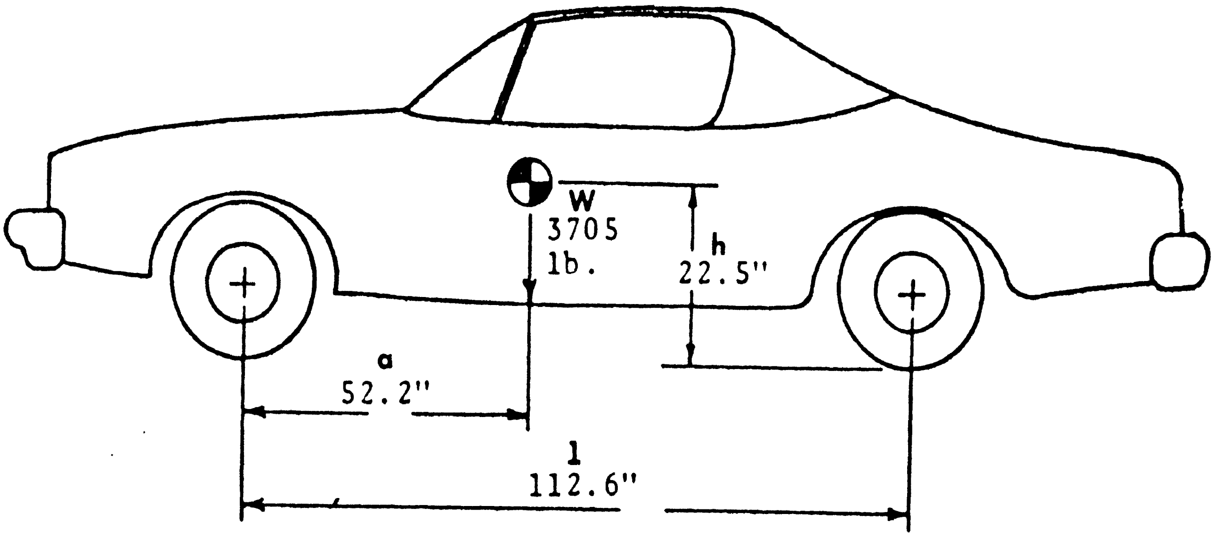

Figure 1. Parameters of the Reference Vehicle

Clearly, these parameters are significant only in determining the mass which is to be decelerated and the vertical load, F_z, which is imposed upon front and rear tires. Only to the extent that the normalized longitudinal force capability of the vehicle's tires will be sensitive to vertical load is it necessary to be concerned with front versus rear tire loading and thus with identification of the cited parameters.

3.1.1 THE SELECTION OF THE REFERENCE TIRE. Having established a definition of the reference passenger car, it was necessary to determine a selection for the representative passenger car tire. Since traction capability was the property which would govern selection of the reference tire, it was clear that the tire's representativeness could not be screened with rigor comparable to the car parameter determination. Further, it was clear that limitations in available data describing tire market distribution as well as traction performance would prevent the identification of a tire whose longitudinal shear force capability represented the mean of the operating tire population. Rather, for purposes of this study a tire would be selected whose traction capability was approximately the average performance of a sample of domestic production tires, and whose size was established by the weight parameter determined for the reference vehicle.

Based upon a set of data which was available depicting the traction performance of a sample of common production tires, a particular belted, bias-ply construction was selected as most representative of average performance. In a set of tests conducted during this study, the longitudinal traction capability of the selected "average" tire (size E78-14) was compared with the performance of the ASTM G78-15 (E501-73) tire over a wide range of surface conditions and velocities. Since both tires were operated at identical load levels, the influence of tire size became irrelevant to the problem of identifying a traction reference tire exhibiting "average" capability. Clearly, the suitability of the ASTM tire for this role was of interest due to its desirable properties as a stable test sample. Based upon the data gathered in these tests, the ASTM tire was judged to possess a traction potential which was sufficiently close to that of the "representative" tire that the ASTM selection could be applied as the reference tire in this study.

3.2 COMPUTATION OF IDEAL STOPPING DISTANCE

The Braking Efficiency Test Technique provides a measure of the test vehicle's braking efficiency as defined by the equation:

$$\text{Eff} = \frac{\text{Ideal Stopping Dist.}}{\text{Measured Stopping Dist.}} \times 100\% \qquad (1)$$

where the "measured stopping distance" is the minimum stopping distance of the test vehicle and the "ideal stopping distance" is the minimum stopping distance which the reference passenger vehicle could ideally obtain, given the friction properties of the reference tire/test-surface combination.

Ideal stopping distance is calculated for a given pavement condition through the computerized solution of a closed form expression relating front and rear tire loads, prevailing velocity, and tire shear force level, in the integration of an elapsed deceleration distance. The computation assumes that an idealized braking process is established in which

a) no brake actuation lag occurs

b) the vehicle's pitch response is instantaneous, and

c) peak shear forces are sustained throughout the stop.

To the extent that these idealizations yield a shorter deceleration distance than is physically achievable in the real world, the computed distance represents a performance level which is indeed ideal and which is thus useful only as a clearly defined reference. Nevertheless, the computed "ideal stopping distance" does rather precisely describe the frictional constraint which would be imposed by the subject surface upon the limit braking performance of an average passenger car.

While the ideal distance value is utilized directly in the braking efficiency determination, any specifications or standards must account for the non-ideal processes by which actual vehicles achieve their limit braking performance through the selection of realistic levels of required braking efficiency performance.

3.3 THE MEASUREMENT OF THE REFERENCE TIRE'S TRACTION PERFORMANCE

Measurement of the peak longitudinal traction capability of the reference tire is necessary in order to implement the calculation of the ideal stopping distance.

Specifically, tire tests must be conducted in order to provide sufficient data to establish the values of the parametric constants describing the traction potential of the reference tire as influenced by both load and velocity. The accomplishment of this task implies the solution of three problems, namely:

1) Establishment of a well designed tire test matrix encompassing appropriate values of test velocity and tire loading.
2) Employment of an appropriate tire test device.
3) Effective implementation of the resulting data.

The tire test matrix involves a set of eight nominal operating conditions at which peak normalized longitudinal shear force data is to be gathered. The eight conditions cover a matrix of two values of vertical load and four values of velocity which are chosen on the basis of an initial sampling of the nominal traction potential of the reference tire on the subject test surface. The two load levels correspond to the hypothetical front and rear tire loads which would accrue if the reference vehicle were operated at the maximum deceleration level permitted by the nominal traction constraint. The test velocities are selected to span the range of velocities covered during a stop from an initial velocity which is chosen as roughly proportional to the measured nominal traction level.

In sum, the tire traction data is gathered over a range of load and velocity conditions such as would be experienced by the tires of the mean-configuration passenger car during an idealized limit stop. Shown in Figure 2, the tire test velocities are selected on the basis of a piecewise linear function of μ_{nom}, the nominal traction level measured on the subject pavement. Shown in Figure 3, the tire test loads are selected to represent front (F_{zF}) and rear (F_{zR}) tire load values, as a load transfer function of μ_{nom}.

3.4 DEVELOPMENT OF A SURFACE FRICTION DYNAMOMETER

The conduct of mobile tire traction measurements, as needed in the braking efficiency method, requires an apparatus which is capable of making repeatable measurements of peak longitudinal shear force while easily varying vertical load. A major portion of the effort of this program was directed toward the development of such a tire test device, technically suited to the needs of the braking efficiency test technique but whose cost did not exceed the market value of commercially-available ASTM skid trailers.

The resulting device, the Surface Friction Dynamometer (SFD) is pictured in Figures 4 and 5. It is a crew cab pickup-based device capable of measuring longitudinal traction performance of passenger car tires in an over-the-road condition. The device will accept 14- and 15-inch passenger car tires and is designed to measure longitudinal shear force characteristics while operating at vertical loads ranging from 400 to 2000 pounds.

The subject tire is located at the rear of the vehicle on the vehicle center line. The tire is suspended by the wheel carriage structure (WC) which is free to move vertically and is otherwise constrained by a pair of low friction, ball

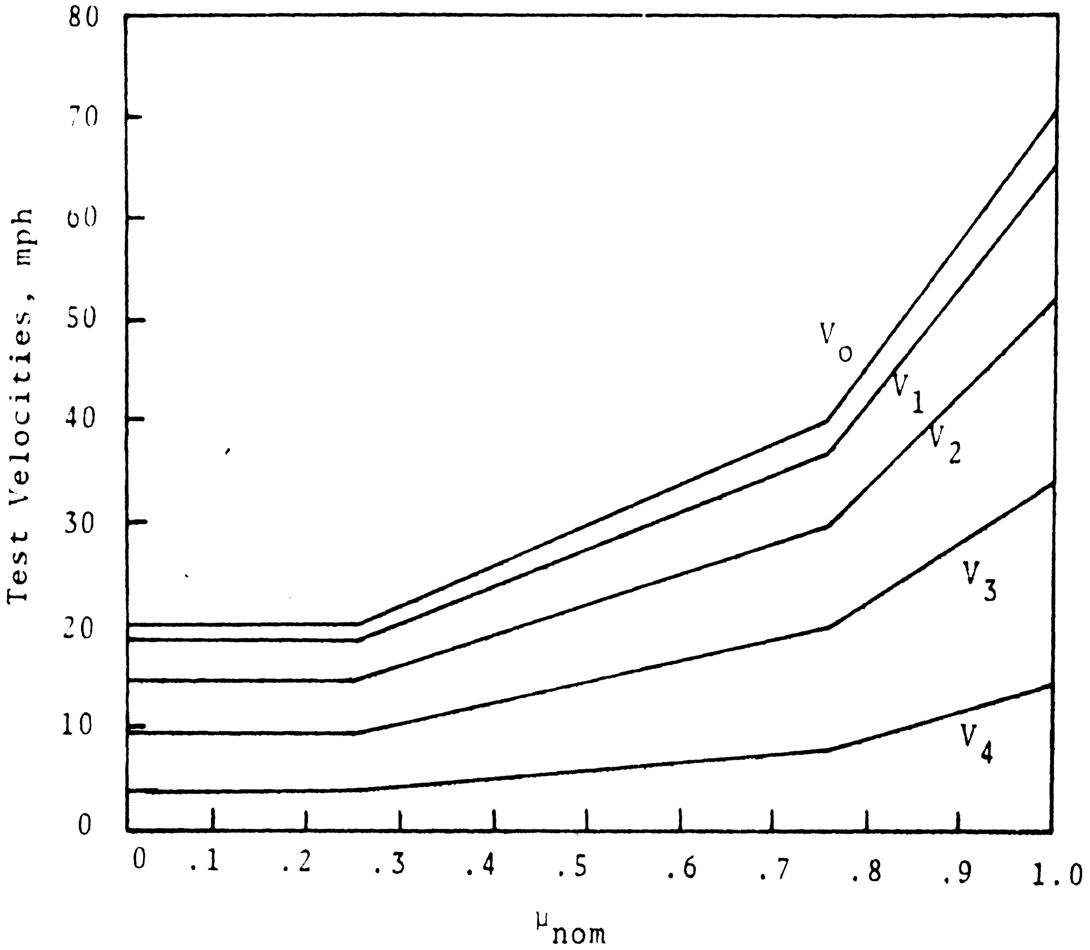

Figure 2. Test velocities as a function of μ_{nom}

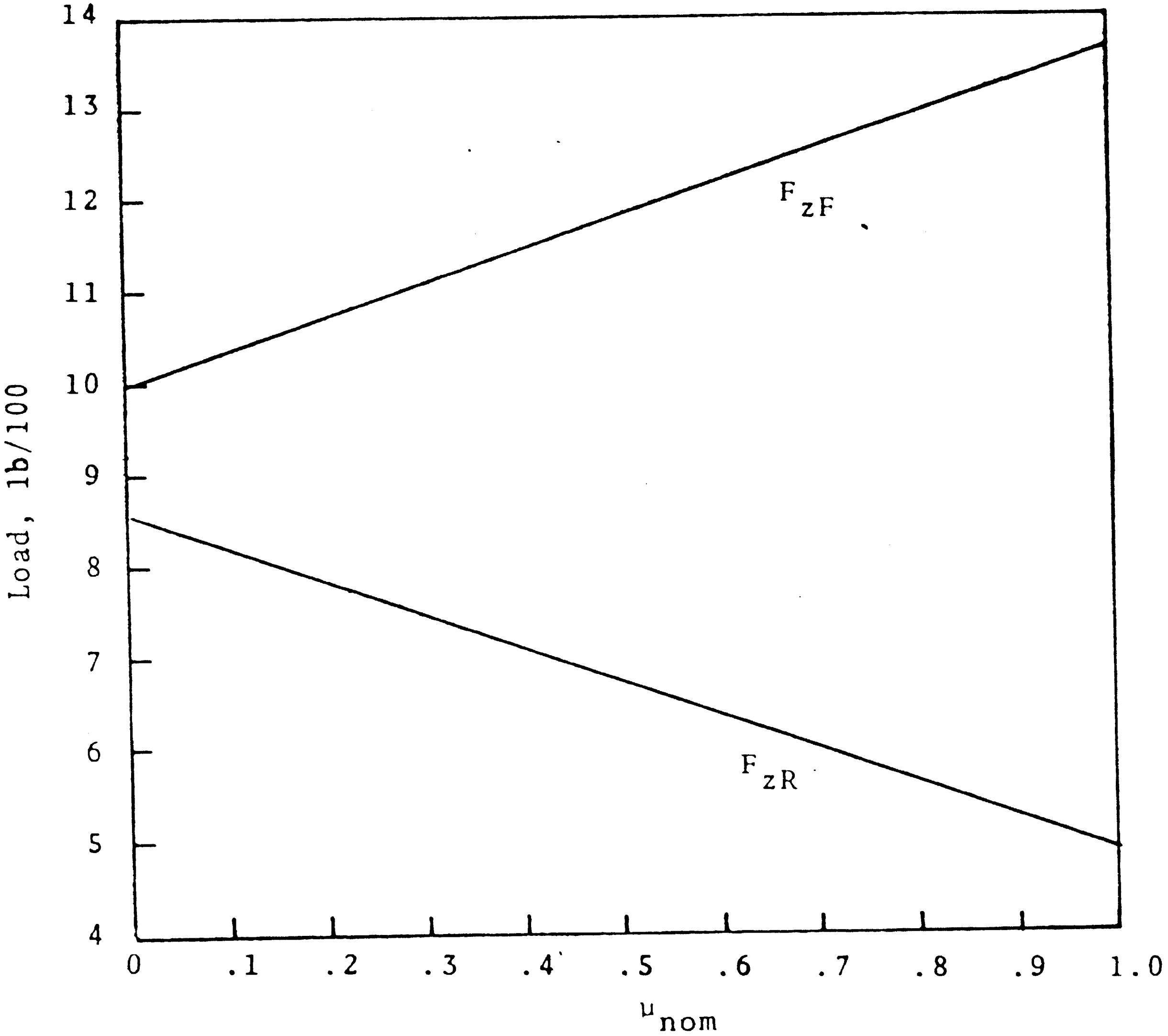

Figure 3. Tire test loads as a function of μ_{nom}

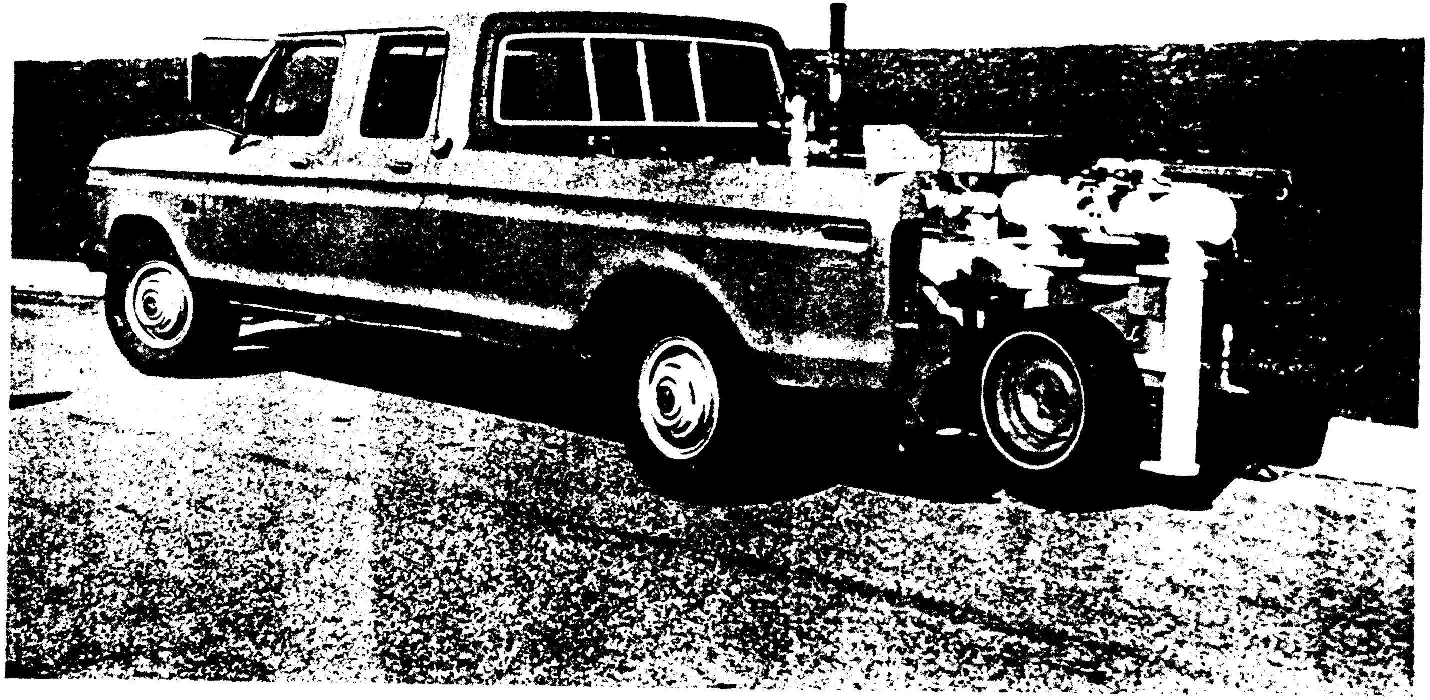

Figure 4. The Surface Friction Dynamometer

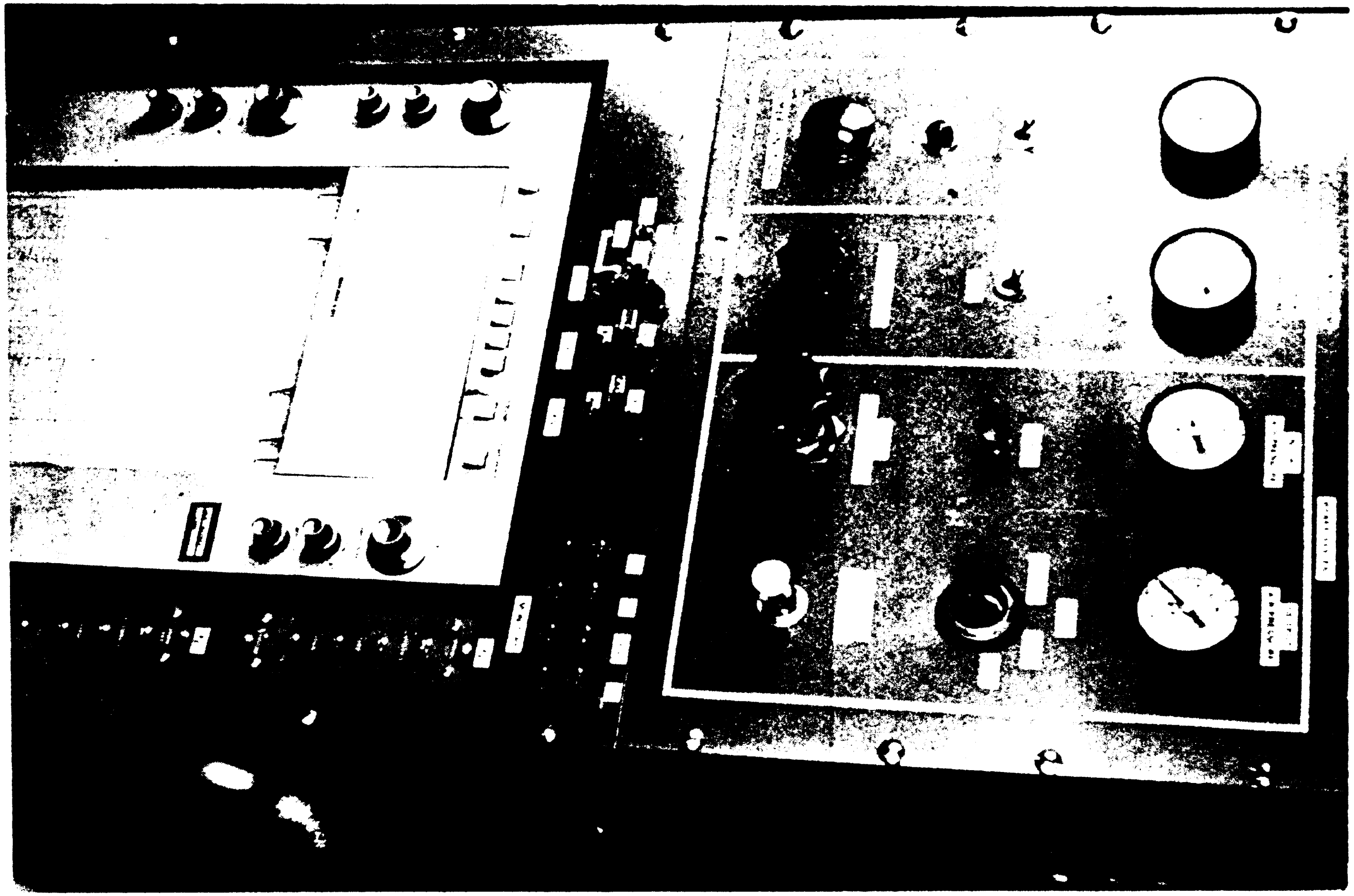

Figure 5. Instrumentation and control module of the Surface Friction Dynamometer.

spline assemblies. A biaxial load cell joins the test wheel spindle assembly to the WC, and transduces vertical (F_z) and longitudinal (F_x) forces. Vertical tire forces are generated by a low rate air spring, bearing on the WC. The test wheel is braked by a single cylinder, floating caliper disc brake.

In order to elongate the spin-down transient of the test wheel for the purpose of recording peak traction performance, the rotational degree of freedom of the test wheel is hydraulically coupled to that of a chassis-mounted flywheel. The effective rotational moment of inertia of the test wheel system is thereby increased roughly tenfold, effecting a similar increase in the response time of this system, thereby facilitating improved accuracy in peak frictional performance measurement. Instrumentation and control devices are located in the rear section of the cab. Continuous analog signals of F_x, F_z, F_x/F_z and vehicle velocity (V) are available for recording (any three concurrently) on a three-channel ink pen recorder. An example F_x/F_z time history is shown in Figure 6, clearly indicating the prolonged peak response which derives from the increased spin inertia of the flywheel system.

As developed, the test device is uniquely suited to the efficient gathering of peak traction data over the matrix of velocity and load conditions as required by the braking efficiency method.

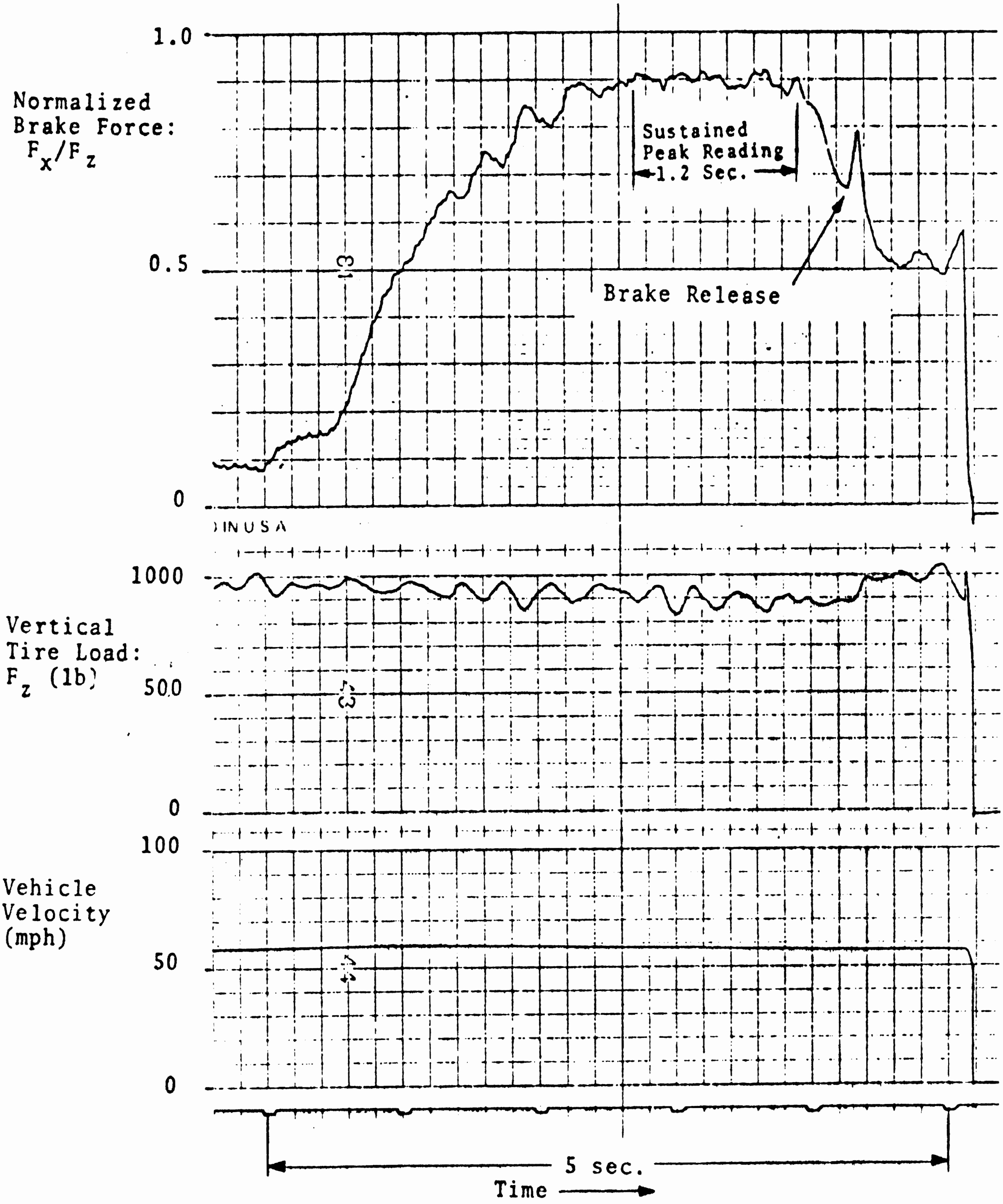

Figure 6. Surface Friction Dynamometer: Example data.

4.0 A DEMONSTRATION TEST PROGRAM

Tests were conducted at the Bendix Automotive Development Laboratories as a demonstration of the overall braking efficiency method. Since the method conceptually applies to any highway vehicle configuration, experiments were conducted on both a hydraulic brake-equipped passenger car and on an air-braked road tractor. The vehicle tests, of course, were conducted to obtain examples of the denominator value in the expression:

$$\text{Braking Efficiency} = \frac{\text{Ideal Stopping Dist.}}{\text{Measured Stopping Dist.}} \times 100\%$$

In addition, the vehicle tests served to demonstrate certain schemes which had been developed to permit constant effort actuation of the brake pedal. For the passenger car, a pneumatic device was employed to provide variable level, sustained force inputs throughout the stop. For the air-braked truck, a mechanical assembly was used which held displacement of the treadle valve to a constant value. The constant effort braking applications were adopted in this study in consonance with a fundamental position which had been taken; namely, that stopping performance quality is enhanced in that tire/vehicle system which demands the minimum in brake pedal modulation while otherwise exhibiting a minimal-length stopping distance. In the absence of data describing driver ability to "hunt" for optimum pedal effort (as this optimum changes throughout a stop), the use of a constant pedal effort procedure was seen as a viable test constraint which accounted the basic position.

An additional object of the vehicle test demonstration involved the objective monitoring of wheel rotation so that lockup could be explicitly defined. A detector assembly with associated circuitry was developed for continuous monitoring of up to ten wheels on a given vehicle. The system requires that lockup be defined, in terms of a condition in which wheel rotational velocity descends below a minimum value, for longer than a prescribed interval of time.

Stopping distance testing of the passenger car and heavy truck was conducted over a matrix of surface and load conditions. Velocities for individual tests were determined on the basis of concurrent measurements of the nominal surface friction condition, μ_{nom}, as indicated previously in Figure 2.

The simultaneous operation of the SFD machine provided not only the needed μ_{nom}, determination, but also the matrix of peak tire traction data as required in the computation of ideal stopping distances for each of the test surfaces employed.

Examples of braking efficiency values computed for the passenger vehicle and truck on various surfaces are shown in Table 1. Although the test data was gathered for demonstration purposes only, the large margin between the car and truck efficiencies is notable. Also of interest is the relatively small influence on overall passenger car efficiencies which resulted from significant changes in brake proportioning. (The proportioning variations were achieved through on-board programming of a servo-controlled brake system—a feature of the HSRI research vehicle which was employed in these tests.)

Table 1

Vehicle	Surface	Brake Proportioning		Load Condition	Braking Efficiency %*
		% Front	% Rear		
Passenger Car	Dry Asphalt	56	44	Nominal**	75.2
	Dry Asphalt	50	50	Nominal	69.1
	Dry Jennite	56	44	Nominal	64.2
	Wet Asphalt	56	44	Nominal	68.9
	Wet Jennite	56	44	Nominal	72.0
	Wet Jennite	62	38	Nominal	70.0
	Wet Jennite	50	50	Nominal	85.4
Highway Tractor	Dry Asphalt	Nominal***		Bobtail	28.4
	Dry Jennite	Nominal		Bobtail	27.3
	Wet Asphalt	Nominal		Bobtail	26.6
	Wet Jennite	Nominal		Bobtail	17.9
	Dry Asphalt	Nominal		GVWR	37.3
	Wet Jennite	Nominal		GVWR	30.5

*Averaged result of five trials.

**Nominal load condition of passenger car included driver plus instrumentation.

***Nominal brake proportioning of highway tractor was the original equipment condition.

5.0 APPLICATION OF THE BRAKING EFFICIENCY TEST TECHNIQUE TO RULEMAKING

The concept developed in this study is founded upon the argument that the only generally applicable braking performance requirement which the highway traffic system imposes upon its constituent vehicles concerns their relative stopping capability, one to another; the traffic system imposes no specific absolute braking level requirement (although in individual traffic conflicts, more braking capability is better than less). In implementation of a concept deriving from this argument, a measure of relative capability has been defined by which a vehicle's performance <u>on any surface</u> can be meaningfully characterized. It is in regard to this "universality" quality that the authors feel the braking efficiency measure to be most worthy of consideration for rulemaking. In contrast to various fragmented approaches toward braking performance specification, the braking efficiency method permits a homogeneous treatment of pavement friction level. Accordingly, the method accounts for all possible test surfaces uniformly—suggesting that the relative performances of vehicles in traffic is just as pertinent to safety on one pavement as it is on any other.

The homogeneity quality of the method would, of course, be foiled if one were to divide the friction range into discrete, non-adjacent segments, for purposes of limiting the test regimes within which a standard might apply. Such a sectionalizing approach has a tendency, in currently defined braking standards, to focus the compliance assessment efforts of the manufacturing community on the measurement of vehicle performance precisely at the conditions of the defined boundaries. A major reason for this focused effort derives from the inability to normalize data taken on non-boundary condition surfaces. The net effect, however, is to foster an evolutionary design process which is concentrated upon performance under narrow and specialized conditions.

In considering the applicability of the braking efficiency method to a performance standard, we advocate an undivided treatment of the pavement friction range. We do recognize, however, that some bounds must be placed upon this range such that lowest and highest friction level requirements can be defined.

It would appear that a reasonable value for the upper limit of the friction range, defined in terms of the μ_{nom} characterization, could be determined on the basis of a highway pavement survey. By such an approach, an SFD-type machine would be employed to gather μ_{nom} data on a representative sample of the nation's dry highway pavements. The resulting measurements would be used as the basis for specifying a reasonable upper friction boundary.

The definition of a lower friction limit, as is presumably achievable in the highway traffic environment under some sort of ice condition, seems to demand that a pragmatic stance be taken in recognition of the absence of a pertinent test technology for ice- or snow-contaminated surfaces. Thus we would not advocate a survey of the nation's wintertime friction conditions, since it is clear that such a survey would identify μ_{nom} values which are well below those levels which could be specified for compliance testing. Accordingly, the lower μ_{nom} boundary for a rule might be based upon measurements taken on wet, coated pavements such as are commonly used in vehicle test practice.

Regardless of the location on the μ_{nom} scale of the upper and lower boundary conditions, performance would be defineable for any surface whose μ_{nom} is within the described range. An example of such a performance rule is shown in Figure 7. One could evaluate performance on whatever surface pavement as might be available—although some attention should be given to surface profile irregularity. Clearly, the number of tests required to assure compliance over the entire friction range would be in direct relation to the vehicle development engineer's ability to analytically interpolate performance between measurements. Spot checking of a vehicle's braking efficiency at only two or three μ_{nom} levels, for example, will be adequate only if there exists a performance-predictive model which permits valid generalization over all values of μ_{nom}.

With regard to the setting of specifications of braking efficiency performance levels, certain considerations should be addressed.

Firstly, the ideal stopping distance computation has, by design, excluded a number of influences which, in an actual vehicle, tend to degrade minimum stopping distance capability. In general, the performance capability of actual vehicles is sufficiently low that any reasonable specification of braking efficiency performance must permit efficiency values well below 100%.

Since the efficiency measure is based upon a representative passenger vehicle reference, a quantitative guide to scaling braking efficiency specifications can easily be established by determining an average of the braking efficiencies of a representative sample of passenger cars on a selection of surface conditions. Using these data as a practical reference, then, one could evaluate the braking efficiency performance of other vehicle classes and determine "allowances" as guided by whatever cost-benefit considerations as are essential to the rulemaking process.

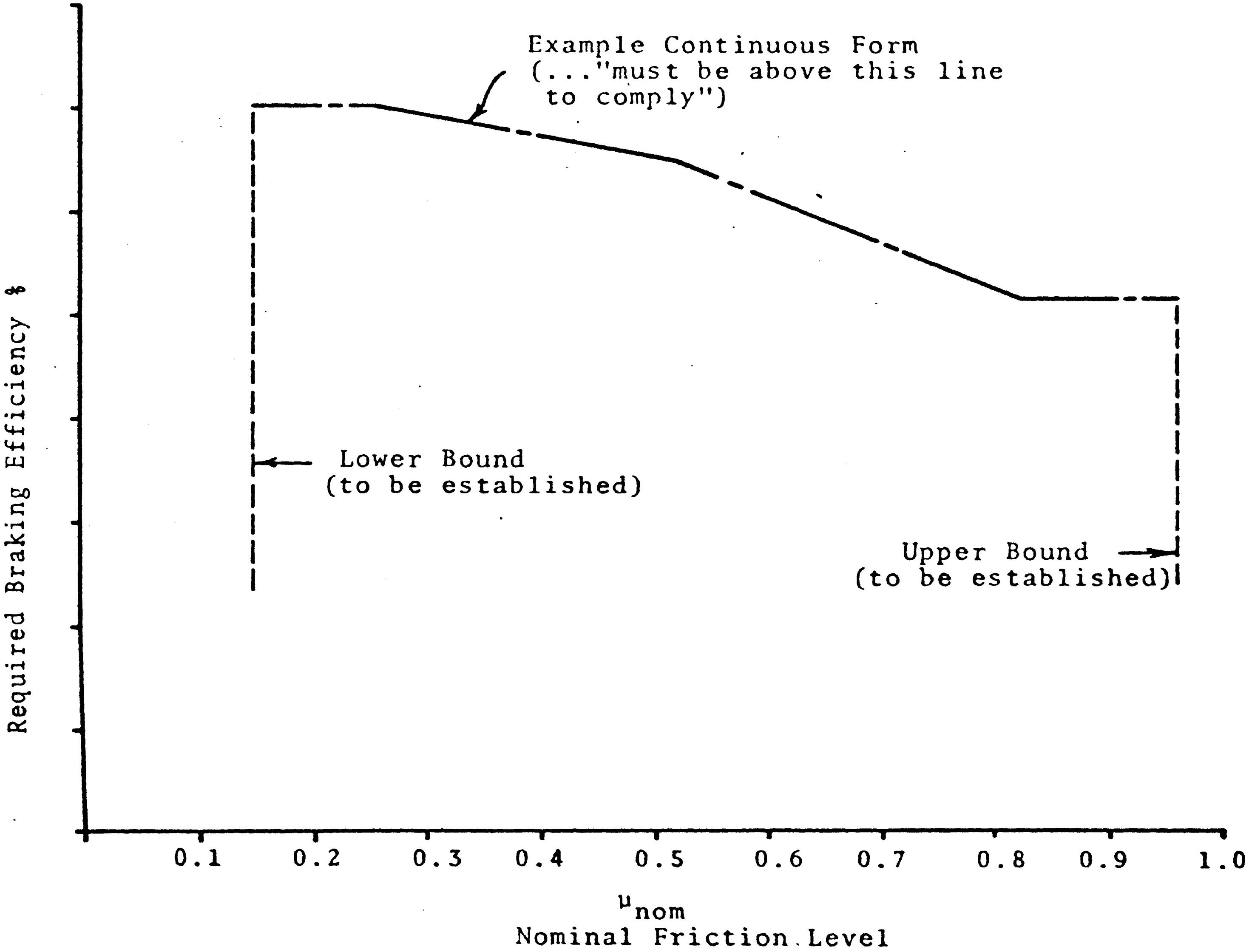

Figure 7. Example braking efficiency requirement showing desired continuous form as a function of μ_{nom}.

In determining the contour of the required efficiency level as a function of μ_{nom}, a continuous form such as shown in Figure 7 would appear to be highly desirable. Stepwise discontinuities in requirement specification across the friction range would offer the manufacturer little or no relief from the more severe of the specified levels. This is the case because of the fact that the mechanics of tire and brake systems offer no discontinuous characteristics which could be fitted to such specifications.

Given that discontinuities would be avoided, then, the actual contour of the efficiency requirement must derive from the judgment of cost-benefit factors. Clearly, one would be led to considering a non-constant efficiency requirement only through the observation that a constant level specification imposes a large gradient in "cost" over the friction range ("cost" here refers to the economic implications of requiring a vehicle performance level which exceeds currently achieved performance levels). If a steep cost gradient is not perceived, then clearly a fixed level braking efficiency requirement is the answer.

A primary consideration in the specification of a braking efficiency requirement involves the extent to which the reference tire exhibits a range of traction capability which does not represent the average passenger car tire's performance. With regard to the ASTM G78-15 tire, for example, the limited data available to this study show a significantly reduced peak traction level on wet coated surfaces, as compared to "average" car tire performance. Clearly, if this tire were to be used as a government-defined reference for braking efficiency, the mismatch between its properties and the desired average-like performance would need to be factored in to the braking efficiency rule. This could be done by adjusting required efficiency levels upwards in those regimes of μ_{nom} in which the reference tire's traction is sub-average and, conversely, by adjusting requirements downwards for that portion of the μ_{nom} range in which the reference tire is above average in traction capability.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

A braking performance characterization has been developed by which the influence of pavement friction becomes normalized to render a measure which is argued to be inherently relevant to traffic safety. Conclusions are presented here which address the quality of this measure as it may be applicable in a standard practice context.

1. The braking efficiency technique presented here is capable in concept (and, as has been partially demonstrated, in practice) of accounting for the prevailing frictional constraints which limit a vehicle's braking performance on any paved surface.
2. The developed concept is such that it is comprehensively applicable to vehicles operated in the United States but it is not international in form due to the fact that the nationally-"representative" passenger vehicle is of markedly different size and weight distribution from one country to the next, with the mean U.S. vehicle probably departing most notably from international mean values of the pertinent parameters.
3. The braking efficiency method itself is totally objective since:
    a) stopping distance performance is evaluated through an open-loop test procedure which is constrained through objective descriptions of initial velocity, wheel lockup, pedal application, and distance measurement, and

    b) the normalizing numeric is derived through a mechanistic process of data gathering and processing.

4. The braking efficiency measurements made during demonstration testing showed the method to be quite repeatable on the short term. Long-term repeatability of braking efficiency measures, it might be argued, depends not upon the testing method itself, but upon the stationarity of pavement frictional characteristics and vehicle braking-related properties.

5. The test burden associated with the braking efficiency technique is somewhat greater than that currently practiced involving braking effectiveness measurement in conjunction with ASTM skid trailer operation. To the extent that skid trailer measurements are made only infrequently by certain test agencies, the continual operation of the Surface Friction Dynamometer in a braking efficiency method might constitute a considerable increase in burden. In perspective, however, the continual accompaniment of stopping distance measurements with SFD measurements would only be required if pavement friction characteristics were seen to fluctuate significantly and often. Indeed, if that were the case, then it would seem that any surface friction characterization, whether skid numbers as required in FMVSS 105-75 and 121, or SFD measurements as in the braking efficiency method, would be required on a frequent basis.

6. The hardware associated with the measurement of the peak traction of the reference tire has been found to constitute a practical and reliable test tool whose data productivity is comparable to skid trailer operation.

7. The cost of the SFD machine would be comparable, in production, to the cost of commercially-available ASTM skid trailer systems (including trailer, tow vehicle, and data acquisition system).

8. The processing of SFD data, and the subsequent computation of the reference vehicle's stopping distance, involves a rather insignificant cost burden.

6.2 RECOMMENDATIONS

On the basis of the developments which have been made during this study, we recommend the following.

1. A program of braking efficiency measurements should be conducted to enlighten whatever rule-making considerations as might ensue from this study. There is a need to:
   a) Establish the performance capabilities of contemporary passenger vehicles to provide a scale for interpreting the braking efficiency numeric.
   b) Establish the performance capabilities of commercial vehicles which are configured with the upgraded braking systems required by FMVSS 121 and 105-75. These data should permit an assessment of the extent to which the braking efficiency performance spread between cars and trucks varies over the friction range.
2. A survey of peak traction measurements should be conducted over a substantial sample of highways to permit definition of a reasonable upper bound, for the range of the variable μ_{nom}, over which a braking efficiency technique would apply.

3. Measurements of the shear force potential of a variety of paved surfaces should be made using the ASTM tire to determine the short- and long-term stability of those characteristics which determine peak traction performance. With these data, an estimate can be made of the frequency of SFD measurements as might be necessary to assure valid characterization of a given surface which is in continual usage as a braking efficiency test facility.

4. In further refinement of the braking efficiency method, work should be done to examine the influence of tire slip rate and load fluctuation on the generation of peak normalized longitudinal force to determine:

    a) the extent to which the delayed spin-down transient of an SFD machine permits measurement of a representative peak traction performance, and

    b) the conditions under which ASTM skid trailer devices, currently in existence, could be acceptable for use in the gathering of traction data for braking efficiency normalization.