UM-HSRI-76-30-2

MOTORCYCLE BRAKING PERFORMANCE

Contract Number DOT-HS-5-01264

Final Technical Report

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December, 1976

Prepared for the Department of Transportation, National Highway Traffic Safety Administration under Contract No. DOT-HS-5-01264. The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the National Highway Traffic Safety Administration.

Technical Report Documentation Page

1. Report No. UM-HSRI-76-30-2	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
MOTORCYCLE BRAKING PERFORMANCE

5. Report Date
December 1976

6. Performing Organization Code

7. Author(s) Robert D. Ervin, Charles C. MacAdam, Yoshinori Watanabe

8. Performing Organization Report No.
UM-HSRI-76-30-2

9. Performing Organization Name and Address
Highway Safety Research Institute
The University of Michigan
Huron Parkway and Baxter Road
Ann Arbor, Michigan 48109

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
DOT-HS-5-01264

12. Sponsoring Agency Name and Address
National Highway Traffic Safety Administration
U. S. Department of Transportation
Washington, D.C. 20590

13. Type of Report and Period Covered
Final
7/75 - 10/76

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A study was conducted to evaluate the existing Federal Motor Vehicle Safety Standard for Motorcycle Braking Systems and to develop an alternate test methodology which resolves certain shortcomings thereof. Full-scale vehicle tests were conducted, per the existing standard, and the alternate test concept was developed and demonstrated. The study finds that a procedure involving a process of towing the test motorcycle does represent a viable approach suitable for adaptation in a next-generation rule concerning motorcycle braking performance.

17. Key Words motorcycle, brakes, tow-test, effectiveness, fade, rulemaking	18. Distribution Statement UNLIMITED

19. Security Classif. (of this report) NONE	20. Security Classif. (of this page) NONE	21. No. of Pages 115	22. Price

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized

☆ U. S. GOVERNMENT PRINTING OFFICE : 1973 725-504/328

TABLE OF CONTENTS

ACKNOWLEDGMENTS

A special acknowledgment is due to the Honda Motor Company for its cooperation in this program. Honda not only provided a test motorcycle and a substantive response to the questionnaire on advanced braking systems, but also contributed the services of a senior engineer, Mr. Y. Watanabe, a co-author of this report. Thanks are also due to Kawasaki Heavy Industries and Suzuki Motor Company for both the loan of test motorcycles and the response to the advanced systems questionnaire. The Harley-Davidson Motor Company is acknowledged for providing a test machine and for providing technical information. The Moto Guzzi Company is also thanked for providing technical data on its Integral Braking System.

Liaison with motorcycle manufacturers was obtained through the gracious assistance of the Motorcycle Industry Council.

We also wish to acknowledge the gracious cooperation of the Salenbien Brothers Company for provision of the tow vehicle employed in demonstration of the revised test methodology. The tow-test apparatus was constructed under the supervision of Mr. J. Boissonneault of HSRI.

Finally, it must be acknowledged that the test program at the Bendix Automotive Proving Grounds was directed by Mr. C. Williamson.

1.0 INTRODUCTION

This document constitutes the final report on a research study entitled "Motorcycle Braking Performance" which has been conducted under Contract Number DOT-HS-5-01264 from the U. S. Department of Transportation (National Highway Traffic Safety Administration).

The purpose of this study has been to conduct and evaluate the existing motorcycle brake systems standard, FMVSS 122, and to develop a revised method which resolves shortcomings in that standard. In formulating HSRI's approach toward this project, a certain premise was adopted—namely, that FMVSS 122 was fundamentally inadequate in areas relating to the objective characterization of motorcycle braking performance. In addition to observations that the standard was conceptually wanting, it also appeared that certain procedural requirements of 122 imposed a substantial level of hazard to the test rider. Accordingly, the project was designed from the outset to permit a large portion of the overall effort to be devoted toward developing a revised test methodology.

The braking performance of four motorcycles, per the procedure of FMVSS 122, was measured, firstly as a means of evaluating the standard itself, and, secondly, to provide a set of test data for use in making judgments concerning test condition specifications.

It should be noted that conceptual inadequacies of the type observed in this standard do not actually require experimental trial for their demonstration. Nevertheless, it was felt that certain portions of the industrial and governmental communities would more readily receive the recommendations resulting from this project if they were cast in the light of relevant test experience.

The primary consideration requiring special treatment of the two-wheeled motorcycle, of course, is its independent actuation of front and rear brake systems. By this feature, the typical motorcycle differs fundamentally from, say, the motor car in the demands it places on a braking performance test. Accordingly, it was felt that the basic requirement for an objective measure of motorcycle limit braking capability was that a means for distributing braking effort be specified. Thus, in the new test concept to be presented, an objective format for brake actuation is the primary feature.

While the major result of this study is the recommendation of a new format for a motorcycle brake system standard, a certain qualification of this recommendation and of the project effort leading to it is in order. This project has been structured to apply the principals of classical vehicle mechanics to the design of a measurement methodology. By the containment of scope within the boundaries of such an engineering discipline, the resulting test technique yields measurements of a form comparable to those produced in other federally-promulgated braking rules, but does not serve to characterize braking quality from a human factors point of view. Insofar as motorcycle braking involves rider control tasks which may be substantially more demanding than is the case for cars and trucks, we might hypothesize that the match between operator skill and vehicle properties is of greater relevance to safety in the case of the motorcycle. Accordingly, while the following report documents a test method which appears to offer a substantial improvement over the existing brake standard, it should be recognized that the resulting measurements very likely do not provide a comprehensive assessment of the safety quality of a motorcycle's braking performance.

The technical discussion in this report is contained within three major sections, viz.:

Section 2 - Application of the existing FMVSS 122 test program to four motorcycles

Section 3 - Development of a unified test method involving a totally new technique for motorcycle braking performance measurement.

Section 4 - Recommendation for a new federal braking standard for motorcycles in which the framework for applying the unified method to a new standard is developed and discussed.

The technical discussion is supported by a set of appendices presenting: motorcycle test data (Appendices A and B); the detailed design of test apparatus supporting the unified test method (Appendix C); information supporting projections of future braking systems (Appendix D); certain analyses supporting the unified test method (Appendix E); and, finally, data describing the traction behavior of motorcycle tires as supports considerations of motorcycle braking in a turn (Appendix F).

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2.0 CONDUCT OF THE FMVSS 122 TEST PROGRAM

The FMVSS 122 tests were conducted at the Bendix Automotive Proving Grounds (BAPG) near New Carlisle, Indiana, on a sample of four test motorcycles. The testing was supervised and conducted by the BAPG staff, utilizing the services of a professional rider. In an attempt to identify qualitative influences of rider skill on minimum stopping distance performance, a short series of rider skill sensitivity tests were also conducted employing two additional riders representing differing levels of riding experience.

2.1 Selection of the Test Motorcycle Sample

As a starting point in the selection process, a survey was conducted on over 95% of the motorcycle market to obtain information and specifications relating to such general items as motorcycle size, usage, brake system, tires, and market representativeness. Each of these items was considered in the selection of a four-vehicle sample.

The final selection process was influenced by the following three principal variables: (1) approximate size (indicated by engine displacement and vehicle weight), (2) brake system configuration (drum front and rear, disc front-drum rear, disc front and rear), and (3) usage (street, trail, street and trail). Although the selection process did account for the additional factors such as market representativeness, stopping distance performance, and tire characteristics, these latter items served as secondary variables.

Table 1 shows the selected sample ranging in size from the smallest bike, a Suzuki 125cc, to the largest, a Harley-Davidson 1200cc machine. Specifications relating to size, brake systems, and tires are shown for each bike.

Table 1. Specification for Test Vehicle Sample

	Harley Davidson FXE-1200	Honda CB 400F	Kawasaki F9C	Suzuki TS-125 (Tentative Selection)
Vehicle Weight with Full Gas Tank, lbs.	580	405	312	230
Wheelbase, inches	62.7	53.3	55.0	51.6
Engine Displ., cc	1200	408	347	123
Engine Type	4 stroke, 2 cylinders	4 stroke, 4 cylinders	2 stroke, 1 cylinder	2 stroke, 1 cylinder
Brake System Config.	Hydraulic Disc Front & Rear	Hydraulic Disc-Front Mech. Drum-Rear	Mech. Drum Front & Rear	Mech. Drum Front & Rear
Total Lining Area-Front	8.8 in^2	4.34 in^2	12.35 in^2	10.8 in^2
Total Rotor Swept Area-Front	113 in^2	89 in^2	21.2 in^2	16.1 in^2
Total Lining Area-Rear	10.0 in^2	16.3 in^2	13.8 in^2	11.0 in^2
Total Rotor Swept Area-Rear	100.1 in^2	23.8 in^2	21.2 in^2	16.1 in^2
Ratio of Total (F.&R.) Lining Area to (Vehicle weight + 150-lb rider)	0.026 in^2/lb	0.037 in^2/lb	0.035 in^2/lb	.057 in^2/lb
Ratio of Total Rotor Swept Area to (Vehicle weight + 150-lb rider)	0.33 in^2/lb	0.20 in^2/lb	0.092 in^2/lb	.085 in^2/lb
Front Tire Size	MM90x19 (infl. 18 psi)	3.00x18 (infl. 26 psi)	3.00x21 (infl. 24 psi)	2.75x19 (infl. 20 psi)
Rear Tire Size	5.10x16 (infl. 24 psi)	3.50x18 (infl. 28 psi)	4.00x18 (infl. 31 psi)	3.25x18 (infl. 28 psi)
Front Reserve, N_{R1}	.73	1.06	1.33	1.39
Rear Reserve, N_{R2}	3.26	3.09	3.60	4.0
Tire Tread Type	Street Tread	Street Tread	"Universal Trials" Tread	"Universal Trials" Tread

As part of the total survey of all motorcycles, there arose the question of whether three-wheeled motorcycles should be surveyed. In order to examine the advisability of including, as part of the test sample, a three-wheeled motorcycle, a separate survey of these vehicles was conducted. The survey of three-wheeled motorcycles (summarized in Table 2) was similar in nature to the survey of two-wheeled motorcycles and provided two important facts:

1) there is nothing inherent to the braking systems of three-wheeled motorcycles which sets them apart from two-wheeled motorcycles as regards straight-line braking dynamics, and
2) all varieties of three-wheeled motorcycles (street and off-the-road) constitute less than 1% of the total volume of motorcycle sales.

Accordingly, it was determined that the goals of the study would be more appropriately served by restricting the vehicle sample to two-wheeled motorcycles.

2.2 Instrumentation

A special instrumentation package was prepared by BAPG for the measurement of the following variables: velocity (including the stored display of the initial velocity occurring coincident with the brake applications at the start of a stopping test); stopping distance (obtained through the use of a chalk-gun device); front and rear brake lining temperatures (using plug-type thermocouples and a calibrated digital display readout); hand-lever force and pedal force (transduced by way of strain-gauged hand levers or packaged pedal force cells, or, in the case of hydraulic front brakes, a calibrated pressure transducer); longitudinal acceleration (using a U-tube monometer display).

Table 2. Three-Wheeled Motorcycle Survey

Name of Company or Mfgr. Description	Dune Allied Mech. Products Cycle Div. Tower Industries	Rupp Industries Inc. Mansfield, Ohio	BGW Industries Mansfield, Ohio	Commuter Industries Cascade, Iowa	OMC Lincoln ("Cushman")
Estimated Sales Volume/Year	1800	1000	175	2500	2200
Cycle Weight	375 lbs	720 lbs	360 lbs	225 lbs	1180 lbs
Wheel Base	102 in	90 in (x 60)	73 in	45 in	72 in
Front Tire Size	3.50 x 13	3.25 x 16	3.50 x 10	21 x 11 x 8	5.70 x 8
Front Tire Inflation Press.	10 psi	28 psi	18-20 psi	3 psi trail 6 psi road	35 psi 55 psi max
Front Tire Tread Type	Trail	Street	Street	Trail	Rib-Street
Rear Tire Size	18 x 9.5 x 8	B60 x 13 (Pass. Car Tire)	18 x 8.5 x 8	21 x 11 x 8	5.70 x 3
Rear Tire Inflation Press.		14 psi	30 psi	3 psi trail 6 psi road	35 psi 55 psi max.
Rear Tire Tread Type	Street	Street (Pass. Car Tire)	Street	Trail	Rib-Street
Front Brake System Config.	Mech. Actuated Drum, Hand Opr.	Mech. Actuated Drum, Hand Opr.	Mech. Actuated Drum, Hand Opr.	Mech. Actuated Drum, Hand Opr.	Hydr. Act. Drum, Hand Opr.
Front Brake Lining Size or Area	5 in Dia. x 1 1/2 in	4 5/8 in Dia. x 1 in	6 in Dia. x 2 in	4 in Dia. x 2 in Wide	17 in^2 area 7 in Dia. x 1 1/4 in
Rear Brake System Config.	Hydr. Disc, Dual, Hand Opr.	Hydr. Disc, Dual, Foot Opr., & Mech. Caliper Parking Brake	Hydr. Disc, Dual, Hand Opr. & Mech. Disc Parking	Drum, Ext. Band, Mech., Hand Opr.	Hydr. Act. Drum, Hand Opr.
Rear Brake Lining Size or Area	2" pad on 6" Dia. Disc	2" Pad on 12" Dia. Disc	2" Pad 7" Dia. Disc	4" Dia. x 2" Wide	17 in^2 Area 7" Dia. x 1 1/4"

In addition to these direct measurement capabilities, electronic circuits were built for the purpose of storing the value of initial velocity which obtained at the time of brake application, the peak values of hand lever and foot pedal forces obtained during the braking interval, and total time of the stop.

2.3 FMVSS 122 Test Procedure

The FMVSS 122 test procedure bears a strong resemblance to its counterpart for passenger cars, FMVSS 105. The procedure is characterized by the following elements:

—pre-burnish effectiveness

—burnish procedure

—second effectiveness

—fade/recovery

—final effectiveness

—wet brake recovery

Table 3 is a summary of the tests performed in this study. Tests No. 1-14 (as listed in the table) constitute the formal sequence of FMVSS 122 tests, while Test No. 15 pertains to the aforementioned rider skill sensitivity tests. The section numbers of the formal 122 test procedure appear in Column 2 of the table, followed by the descriptive title of each particular test, the number of stops required, the initial velocity of each stop, and the specified braking level. All tests required by the 122 procedure, except for the burnish sequence, were conducted by a professional rider.

The rider skill sensitivity tests (Number 15 in the test schedule) were conducted at the end of the FMVSS 122 tests, utilizing two additional riders, selected on the basis of their

Table 3. Matrix of Tests Conducted as a Trial of FMVSS 122.

Test No.	122 Proc. No.	Test Description	No. of Stops	Velocities	Acceleration Level
1	S7.2	Pretest instrument check	10	30 mph	10 fpsps
2	S7.3.1	First (preburnish) effectiveness Total service brake system	6 6	30 mph 60 mph	Min. stopping distance (Covering maximum system performance)
3	S7.3.2	Pre-burnish Effect. Front	6 6	30 mph 60 mph	Min. stopping distance (Covering maximum system performance)
		Pre-burnish Effect. Rear	6 6	30 mph 60 mph	
4	S7.4	Burnish Procedure	200	30 mph	12 fpsps
5	S7.5	Second Effectiveness	6 6 4 4	30 mph 60 mph 80 mph highest speed minus 4 to 8	Min. stopping distance (Covering maximum system performance)
6	S7.6.1	Baseline Check	3	30 mph	10 to 11 fpsps
7	S7.6.2	Fade Stops	10	60 mph	15 fpsps
8	S7.6.3	Recovery Test	5	30 mph	10 to 11 fpsps (plus max. system deceleration)
9	S7.7	Reburnish	35	30 mph	12 fpsps
10	S7.8.1	Final Effectiveness Total service brake system	6 6 4 4	30 mph 60 mph 80 mph highest speed minus 4 to 8	Min. stopping distance
11	S7.8.2	Partial service brake system test - Front only	6 6	30 mph 60 mph	Min. stopping distance
		Rear only	6 6	30 mph 60 mph	
12	S7.9	Parking Brake (3-wheeler only)			30% grade
13	S7.10	Baseline Check Stops	3	30 mph	10 to 11 fpsps
14	S7.10.2	Wet Brake Recovery Stops	5	30 mph	10 to 11 fpsps (plus max. system deceleration)
15	To be conducted by: 1) least skilled (but nevertheless experienced rider)	Rider skill Sensitivity Assessment-Effectiveness of Total Braking System	6 6	30 mph 60 mph	
		Front only	6 6	30 mph 60 mph	
		Rear only	6 6	30 mph 60 mph	
	2) medium skilled				

respective amounts of riding experience. Minimum stopping distance data obtained with these two riders, together with the final effectiveness stopping distances obtained in the 122 tests by the professional rider, constituted the basis for assessing the influence of rider skill on the outcome of the test.

2.4 FMVSS 122 Test Results

In the following subsection, generalized conclusions are drawn from the data obtained in the formal sequence of FMVSS 122 tests. The data supportive of this discussion is contained in Appendix A.1. Conclusions which are derived from these test results should be seen as tentative insofar as the vehicle sample contained only four motorcycles.

2.4.1 Ease of Compliance. The most visible result of all the 122 tests was the substantial margin of compliance indicated in most performance categories with each bike when operated by the professional rider. In stops from 60 mph, for example, typical stopping distance performances fell in the range of 150-170 feet, compared to 122's pre- and post-burnish effectiveness requirements of 216 and 185 feet, respectively.

The only significant challenge to the professional rider's skills, as presented by the 122 stopping distance requirements, occurred in certain of the 30-mph stops. Reasons for the greater challenge at 30 mph than at higher speeds are that (a) the time interval needed to achieve a steady deceleration condition represents a greater percentage of the total stopping time and thus requires a higher sustained acceleration at lower speeds (hence, any hesitance in the rider's brake application transient is more critical in the lower speed stops) and (b) the 30-mph stopping distance requirement of FMVSS 122 implies a nominal deceleration level which is 7% greater than that required at 60 mph.

While it is noted that the professional rider failed the second effectiveness tests at 30 mph on both the Honda and Kawasaki motorcycles, both the pre-burnish and final effectiveness tests were passed easily on both these bikes. As shown in Figures 1 and 2, data from the six "repeat" runs on both of these motorcycles indicate that the 122 requirement was missed by only a few feet in at least one stop on each machine. The data further reveal the extent of repeatability in the stopping distance result as it derives, in part, from the repeatability of the rider's actuator force inputs.

In the case of the Honda (Fig. 1), the non-compliance in second effectiveness tests appears to be explained by the fact that the rider applied considerably less front braking (as indicated by front actuator forces) during the second effectiveness attempts than during the pre-burnish and final effectiveness tests. The reason for the lower performance, shown in Figure 2, during the Kawasaki second effectiveness tests is not as clear, however, since the lower brake actuator force levels were indicated during the pre-burnish and final effectiveness tests. A general loss of brake effectiveness with the Kawasaki does not appear to explain the non-compliant second effectiveness stops from 30 mph since the higher speed and single-wheel second effectiveness tests all approximated the pre-burnish and final effectiveness results. The most likely explanation is simply that of variable rider performance—apparently as regards the delay in brake actuation prior to achieving the necessary deceleration condition.

2.4.2 <u>Hazards of High Speed Stops</u>. The 122 procedure, as indicated earlier, requires that the second and final effectiveness tests be conducted at elevated speeds, including a maximum speed just below that attainable in a one mile distance from a standing start. Although all high-speed tests conducted in this study yielded stopping distances which complied with the standard, the element of hazard to the test rider was quite apparent. In

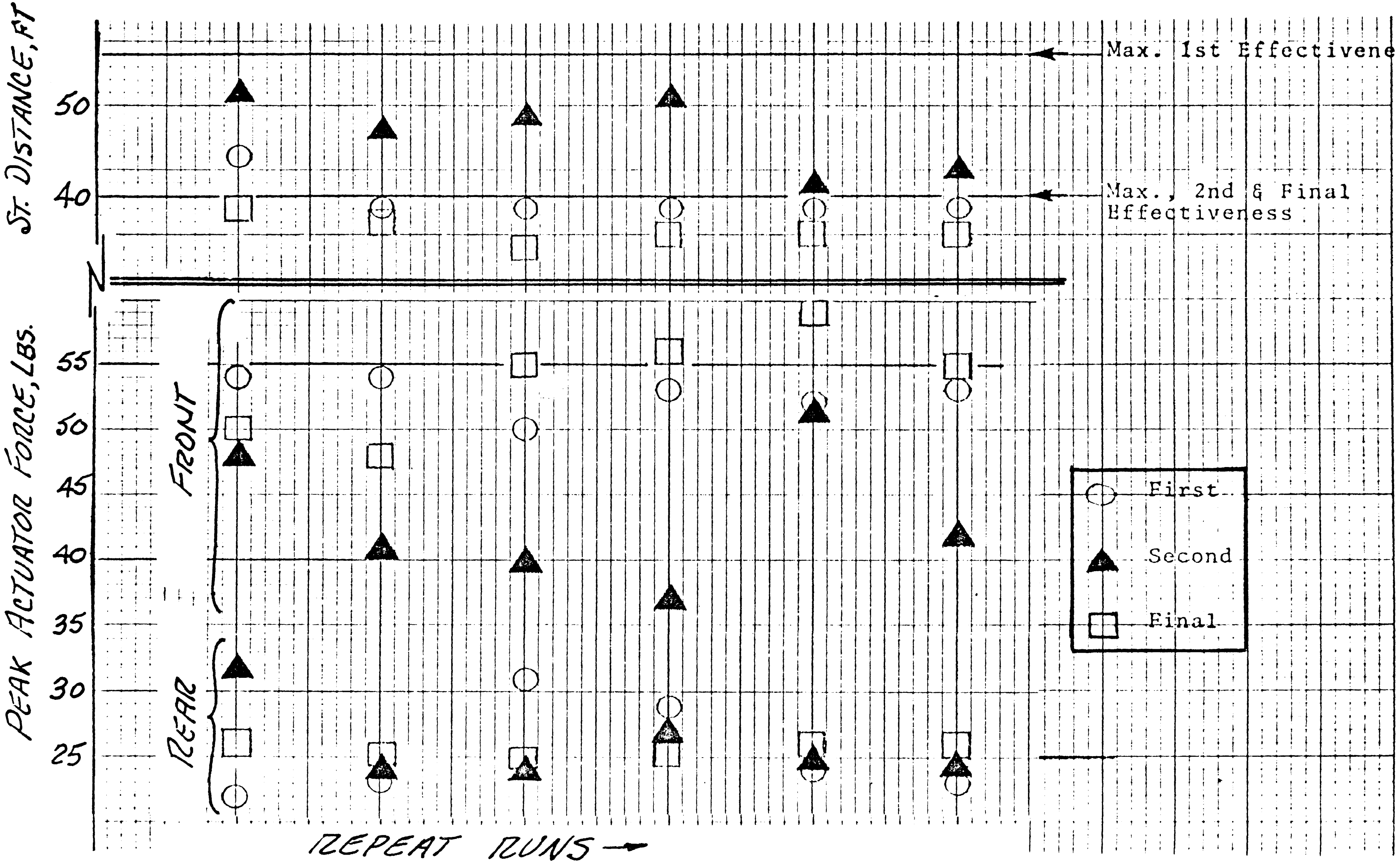


Figure 1. 30 mph effectiveness test results - Honda CB400F.

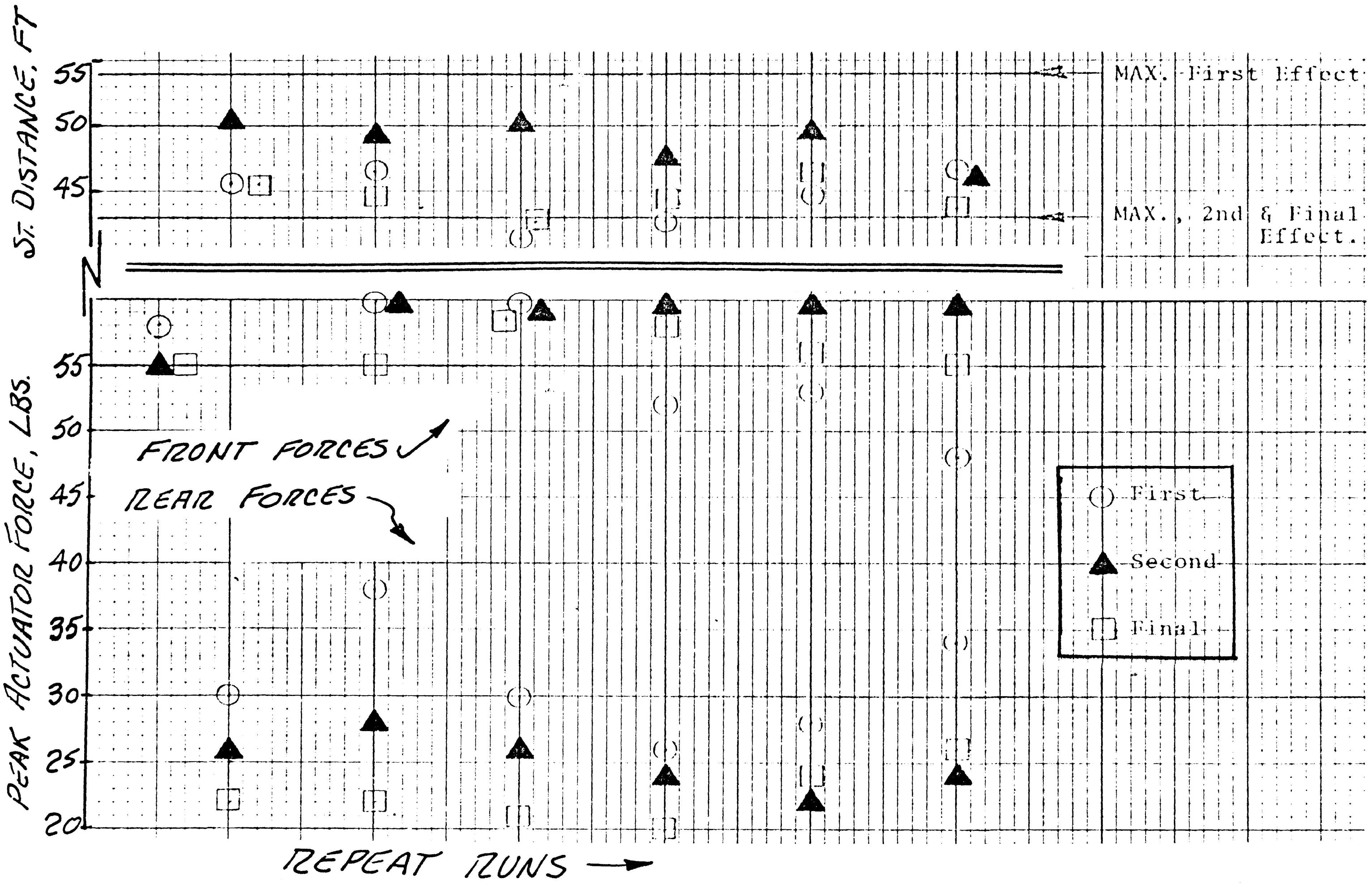


Figure 2. 30 mph effectiveness test results - Kawasaki F9C

testing of the Harley-Davidson vehicle from an initial speed of 105 mph, the professional rider did cause a front-wheel lockup upon first application of the brakes. Fortunately, he quickly recovered control, although this condition would normally have resulted in a spill with riders of lesser skill.

A considerable amount of informal testimony from industry sources indicates that the above-cited experience is not uncommon and occasionally results in a serious injury-producing accident. Accordingly, it would seem that the unique nature of the two-wheeled motorcycle, especially as regards the hazards imposed by wheel lockup at high speeds, calls for a review of the need for performance requirements at such highway-illegal speeds.

2.4.3 Influence of Burnish and "Fade"-Type Work Inputs. A major observation of the 122 testing was a general insensitivity of brake torque effectiveness to the work history provided by the burnish procedure and to the thermal loading incurred during the fade and recovery tests. Inspection of brake linings following burnishing, for example, indicated only a light degree of "seating" of the wearing surfaces. More significantly, though, comparison of most single-wheel pre- and post-burnish effectiveness data shows more variation among the test repeats than between the pre- and post-burnish averages of these repeats. Although it is difficult from the data to determine whatever small changes in effectiveness as may have accompanied burnishing, it is clear that significant changes did not occur.

With regard to the fade/recovery tests, no brake demonstrated a significant sensitivity to the imposed thermal loading. Even though temperatures exceeded 300°F on some brakes, the actuator force levels remained relatively unchanged from baseline to the subsequent recovery tests.

2.4.4 Response to the Wet Brake Recovery Procedure. The immersion-type wetting procedure of FMVSS 122 was found to severely reduce the torque effectiveness of drum-type brakes. The sensitivity of torque effectiveness to the water immersion procedure is assessed through comparison of required actuator forces before and after the water immersion. All drum brakes, as measured by the recovery test sequence, suffered a residual loss of effectiveness following the water immersion. The degree of residual effectiveness change was significant for each brake, but particularly so in the case of the Suzuki front brake, as shown in Figure 3, resulting in failure for this bike to comply with the rather generous range of acceptance allowed by the 122 standard. The apparent explanation for the indicated loss in brake gain is that the immersion condition provides a hydrostatic pressure mechanism for forcing water past the drum brake assembly's dust seal. Upon removal of the vehicle from the immersion tank, a prolonged drainage period is needed. Given this observation, it might be argued that the positive pressure condition is unrealistic for highway-type riding and thus constitutes an artificial assessment of wet-weather braking quality.

Disc brakes were also found to be affected by the water immersion test, but less so in degree and only temporarily. Loss of effectiveness was noted for each of the disc-braked motorcycles during the first one or two of the recovery stops. However, following these initial stops, the performance of each of these vehicles returned to an effectiveness level consistent with the pre-immersion baseline results.

2.4.5 Miscellaneous Observations. The following observations are regarded as secondary in importance but nevertheless noteworthy with regard to FMVSS 122-related concerns.

1) The 55-lb limit on front actuator force was approached or exceeded on all test motorcycles. Contemporary motorcycles thus seem to require virtually all of that allowance to satisfy the stopping distance requirements.

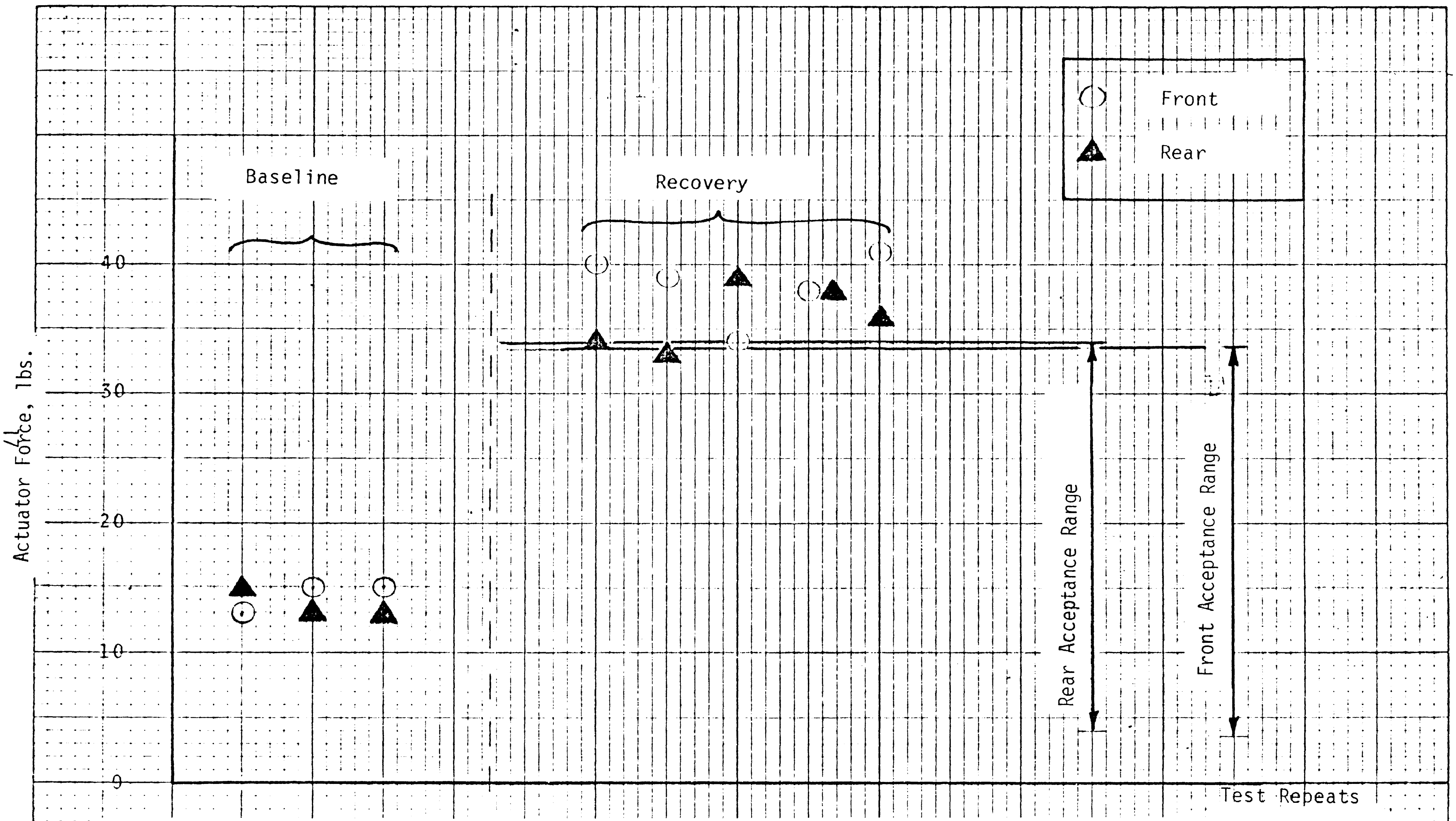


Figure 3. Water recovery results - Suzuki TS-125.

2) The 90-lb actuator foot pedal force limit was never exceeded or even approached during any of the full system tests. Indeed, the highest measured value of foot pedal force was 58 lbs. Our observation is, however, that the 90-lb limit itself may be questionable as an ergonomic minimum—not because the typical rider may be incapable of achieving it, but rather because of the gross motion of the rider's torso needed to generate such a force level. It would appear that such motions are probably in conflict with the already complex control tasks involved in limit braking of motorcycles.

3) Aside from a few cases, actuator forces applied by the professional rider displayed a high degree of repeatability during the final effectiveness tests.

4) The average levels of front-brake actuator force for the 60-mph stops were 10-15% below the levels applied at 30 mph. A possible explanation could lie in the rider's natural aversion to overbraking the front wheel at elevated speeds.

5) The stopping distances obtained during test repeats on each bike varied less than ±5% from their respective averages.

2.5 Rider Skill Sensitivity Test Results

The data from the rider skill sensitivity tests is contained in Appendix A.2. These tests involved conduct of the minimum stopping distance procedure by three riders of skill levels classified as (1) professional, (2) skilled, and (3) novice. Each of these classifications are reflective of an assumed level of riding skill deriving from riding experience. Resumes summarizing the riding experiences of each rider are included at the end of Appendix A.2.

General observations of the rider skill test results follow.

1) A most significant finding of the rider skill tests derives from the different riders' abilities to achieve performances which comply with FMVSS 122. It was seen that:

    a) the professional rider passed all stopping distance requirements

    b) the skilled rider passed about half of the stopping distance requirements—failing the Honda/30 mph, Kawasaki/60 mph, and Suzuki tests at both initial speeds

    c) the novice rider passed all stopping distance requirements but the Honda/60 mph test.

2) The professional rider made greatest use of the front brake, while the skilled and novice riders, apparently for lack of confidence in controlling front-wheel braking, made greater use of the rear brake. One might conclude from the superior overall performance of the professional rider that a test rider's skill in conducting 122-type effectiveness tests depends upon the degree and consistency of usage of the front brake.

3) The margin of superiority of the professional rider over the skilled and novice riders, particularly demonstrated in stopping distance capability, increased at higher test speeds.

4) The repeatability in stopping distance and brake actuator forces attained by the professional rider far exceeded that of the skilled and novice riders.

5) While the novice rider occasionally equaled or exceeded the professional rider's best performance, he also displayed the greatest variation in performance.

6) The skilled rider displayed generally poorer but more consistent stopping distance performance than the novice rider.

3.0 A NEW METHODOLOGY FOR MEASURING MOTORCYCLE BRAKING PERFORMANCE

In this section, the developed test method is presented. This presentation is initiated, in Section 3.1, with a generalized discussion of the features needed in a test methodology suitable for measuring motorcycle braking performance. In Section 3.2 the conceptual basis for the method developed in this study is articulated, describing the various features of the technique and formulating the kinematic relationships which establish the rules for specifying control input conditions and for interpreting vehicle braking reactions. Next, the concept is formalized, in Section 3.3, as a step-by-step test procedure, incorporating the above-described theoretical basis within a practical sequence of tests. The rationale behind various details of the test procedure is presented in Section 3.4. Section 3.5 presents the findings obtained in the program finally conducted as a full-scale demonstration of the newly-developed test procedure.

3.1 General Features of a Suitable Method

The suitability of any braking measurement method can be decided ultimately on the question of whether it actually achieves a set of characterizations which are relevant to a set of vehicle braking performance qualities which have been defined. Beyond the characterizations, themselves, a measurement method can further be evaluated on the basis of its procedural virtues, namely, accuracy, repeatability, practicality, test safety, and the like. The scenario of federal rulemaking also requires that measurements be obtained by way of an objective format.

With regard to the motorcycle, it would appear that the braking performance qualities relevant to highway accident avoidance include the following:

1. Total vehicle deceleration capability which permits a utilization of the available pavement friction potential to a degree which is comparable to that achieved by other vehicles in the highway system.
2. An adequate retention of the vehicle's basic deceleration capabilities under conditions of:
    a) severe thermal loading
    b) exposure to rain and traffic-generated water spray.
3. An appropriate match between the ability of representative riders to manipulate braking control elements and the requirements which the vehicle imposes for braking effort modulation.

In examining the above performance qualities we observe that the motorcycle with independent front and rear braking controls represents a unique case among highway vehicles. Thus, it would appear that an objective characterization of the above qualities requires that the uniqueness of the typical motorcycle be specifically addressed. If objectivity is to be assured, the test rider must be constrained in his distribution of front and rear braking efforts. If test safety is to be assured, the consequences of front wheel lockup must be realized, and a method must be employed which permits assessment of front-wheel braking limits without hazarding a spill. To the extent that a motorcycle's brakes must themselves be exercised to achieve a desired test condition, such as through a "burnish" or "fade" procedure, a method is needed which can rationally and precisely apportion the work or energy input loading between front and rear brakes. Additionally, insofar as motorcycle brakes may be sensitive to water such as becomes delivered to rubbing surfaces during riding, a test method is needed which provides a realistic dynamic wetting condition.

The characterizations of performance which derive from these tests must be interpretable in the context of accident avoidance qualities of actual motorcycles in usage by representative riders. At the current stage of safety research, no solid links have been established between performance properties of motorcycles and the resulting safety qualities. Accordingly, characterizations of vehicle performance must be interpreted in the light of certain intuitively-based hypotheses concerning safety relevance.

One area in which no intuitive basis seems to exist to guide interpretations of performance is in regard to the force and displacement gain characteristics of brake input elements, as they enhance or degrade the rider's ability to achieve desired levels of braking without wheel lockup. While ergonomic limits have been placed on maximum levels of application force, gain-related questions cannot be answered within current technology.

The foregoing discussion sets the scene for a test methodology which appears to resolve many of the problems which arise when traditional methods of motor vehicle testing are applied to the motorcycle.

3.2 Conceptual Basis for the Developed Method

A test methodology which is conceived as providing all of the elements of an objective procedure for motorcycle brake testing has two basic features, viz.,

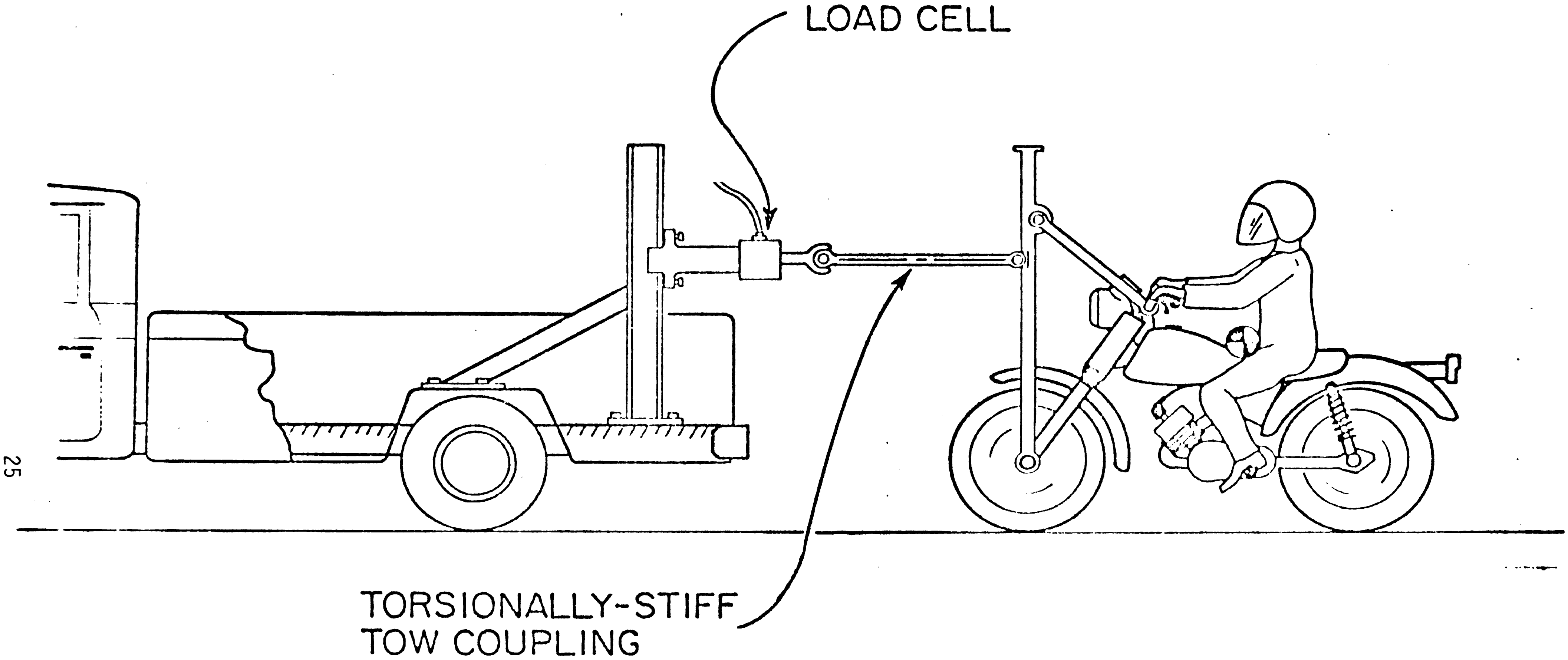
1. the test motorcycle is towed by a support vehicle at constant velocity for all of its dynamic performance measurements, and
2. all tests are conducted with braking control effort being applied to only one actuator at a time.

The tow-test method renders a tow force measurement as its fundamental performance measure. Knowing the total weight of motorcycle and rider, the force measure is interpreted in normalized form as an equivalent deceleration. The attachment of the test motorcycle to a tow vehicle, as conceptualized in Figure 4, involves a roll-rigid coupling, such that the tow vehicle provides roll stability to the motorcycle thereby permitting indiscriminate lockup of front or rear wheel. The test motorcycle is mounted by a rider whose only function is to provide control inputs to the brake actuators according to a prescribed sequence.

As illustrated in Figure 5, the tow vehicle itself incorporates all signal conditioning, power supplies, and recording instruments which would normally be carried on board the test motorcycle in conventional methods. The only test variable displayed to the rider is the tow force. The various experiments are thus arranged around the level and duration of developed tow force, together with prescribed test velocities, for each of a sequence of front-only and rear-only applications.

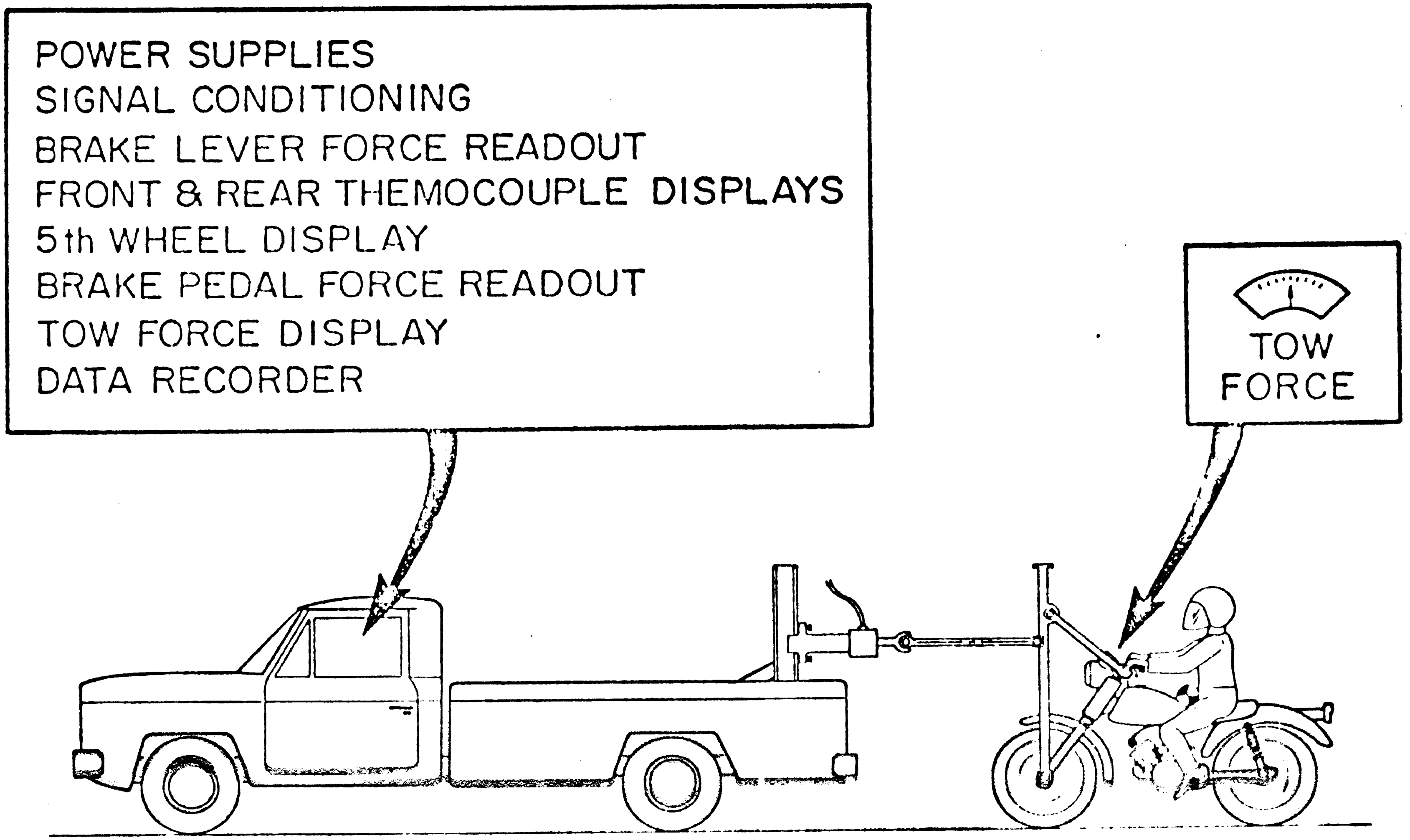
3.2.1 Features of the Test Procedure. The outlined concept for measuring motorcycle braking performance has been developed into a test procedure. The procedure contains the basic elements such as have comprised SAE braking tests, and subsequently, federal braking standards for passenger cars and motorcycles. Thus, in formulation of the unified test concept, a (topically familiar) set of dynamic tests has been defined as follows:

1. pre-burnish effectiveness
2. burnish sequence
3. post-burnish effectiveness
4. thermal loading (fade) sequence with accompanying faded effectiveness assessment
5. wet conditions sequence with accompanying wetted effectiveness assessment.



BASIC TOW-TEST MECHANISM

Figure 4



LOCATION OF TOW-TEST INSTRUMENTS

Figure 5

As far as the tow-test method is concerned, this sequence can be viewed as comprising three fundamentally differing kinds of procedures. The first may be called "conditioning procedures" by which the front and rear brake actuators are applied, in turn, to effect loading histories which represent either burnishing or fade conditions. Secondly, effectiveness measurements can be viewed as means of assessing the limit braking capability of each wheel's brake system. Given an ergonomic limit in force applied at the brake control elements, the "effectiveness" of a front or rear wheel brake system is measured as the peak value in tow force which can be achieved within the limitation on control inputs. The third basic procedure involves the delivery of water to create a dynamic spray representative of a wet weather riding condition. Thus it could be viewed as a special sort of conditioning procedure.

The seven-step sequence of tests thus involves an alternating series of conditioning and effectiveness procedures. The pre-burnish effectiveness test is, of course, intended to provide an assessment of the limit braking capability of the vehicle in its "as-new" state. The measurements of tow forces achieved by front and rear wheel braking are employed to determine the limit capability of the total vehicle, by means of a reduction scheme to be discussed later.

Conditioning Procedure

The "burnish" and "fade" conditioning procedures each involves a series of constant velocity, quasi-constant tow force conditions which are intended to work the friction brakes themselves to achieve the two respective operational states. The wet weather condition is obtained by towing the test motorcycle in an environment of wetted pavement and airborne spray.

The burnish test is modeled after the SAE procedure to the extent of providing 200 cycles of brake application but involves a constant velocity condition and an objective apportionment of front and rear braking. The apportioning technique is based upon a fixed ratio of the tow force, F_x, to that value of dynamic vertical load, F_z, which would accrue at front and rear wheels during a normal stop at a longitudinal acceleration level, A_x/g. During front-brake burnish applications, the test rider modulates his hand lever effort to sustain a tow force whose level is described by the following relation:

$$F_{x_f} = \frac{A_x}{g} \left[\frac{(b + A_x h/g)W}{a + b}\right] \tag{1}$$

where the vehicle parameters, a, b, h, and W, are defined in Figure 6.

The expression in brackets in Equation (1) represents the dynamic front tire load such as would accrue in an actual stop at a deceleration level of A_x/g. Note that the load value expressed in brackets is greater than that which actually occurs in a front-only tow test in which the tow force is sustained at the value shown (and in which the tow coupling is attached at a height equal to the height of the center of mass).

Burnish applications of the rear brake follow a similar scheme of tow force adjustment, reflecting the rear tire load which is achieved in the equivalent stop per the relation:

$$F_{x_r} = \frac{A_x}{g} \left[\frac{(a - A_x h/g)W}{a + b}\right] \tag{2}$$

The burnish conditioning sequence has been conceived as a series of alternating front and rear applications at respective F_{x_f} and F_{x_r} tow force levels. Each application is sustained for a period of time related to the nominal stopping time associated with the reference level of deceleration and the reference initial velocity, V_0. In order to obtain an energy input level at

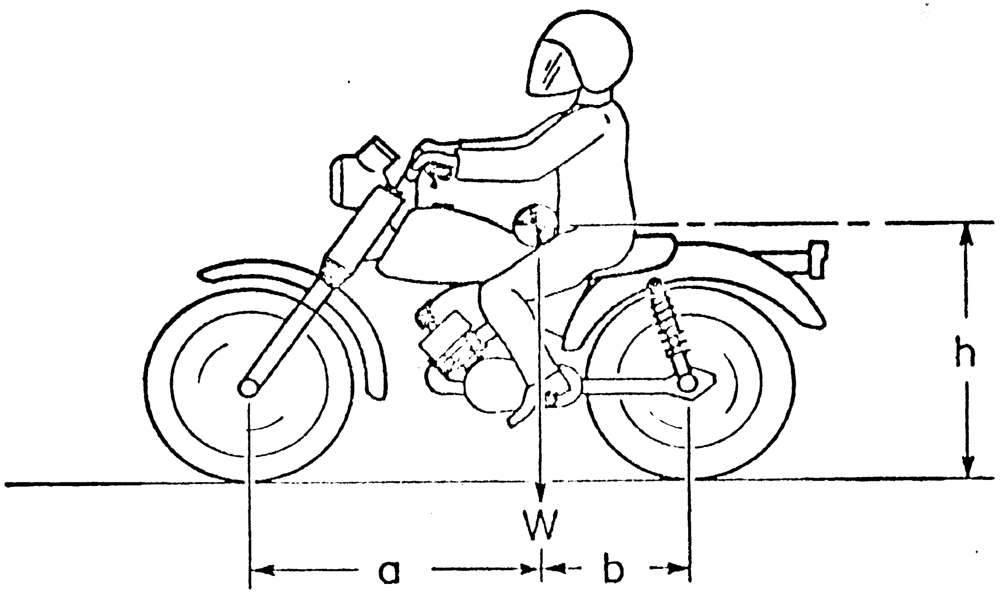


Figure 6. **Basic Mass Center Location Parameters on the Two-Wheeled Motorcycle**

constant test velocity which is equivalent to that accrued through a constant deceleration from V_0 to zero, the steady tow force must be sustained for a traveled distance of

$$d = \frac{V_0^2}{2A_x}$$

The basis for a "fade" conditioning procedure is analogous to that of the burnish method. Front and rear brakes are each in turn exposed to a sequence of applications involving a prescribed level, duration, and frequency of inputs, within which a "faded effectiveness" measurement is obtained on the "heated" brake system. Since the towing technique permits an equilibrium braking experiment, the "faded effectiveness" can be evaluated directly from the heating sequence data, thereby characterizing performance as it actually obtains for the thermally "loaded" system. "Effectiveness" in this case is defined in terms of front and rear control input forces required to sustain reference levels of tow force.

The wet weather condition procedure involves a feature of the towing support vehicle which is peripheral to the tow and data acquisition features. As diagrammed in Figure 7, the tow vehicle concept incorporates a water storage and delivery system which is configured to provide a realistic wet weather condition. As shown, the water delivery system dispenses a stream onto the pavement in line with the wheel path as well as a stream above the ground—in the form of a dense spray. Together, the two-nozzle system is intended to provide a thorough, yet authentic, impingement of water on brake assemblies, such as may occur during a one-inch/hour rainfall on a trafficked highway.

The nozzle which is directed toward the wheel path is configured to provide a constant water depth at the selected speed. The provision of a wetted pavement is seen as a necessary component of the wet condition since a significant element of the

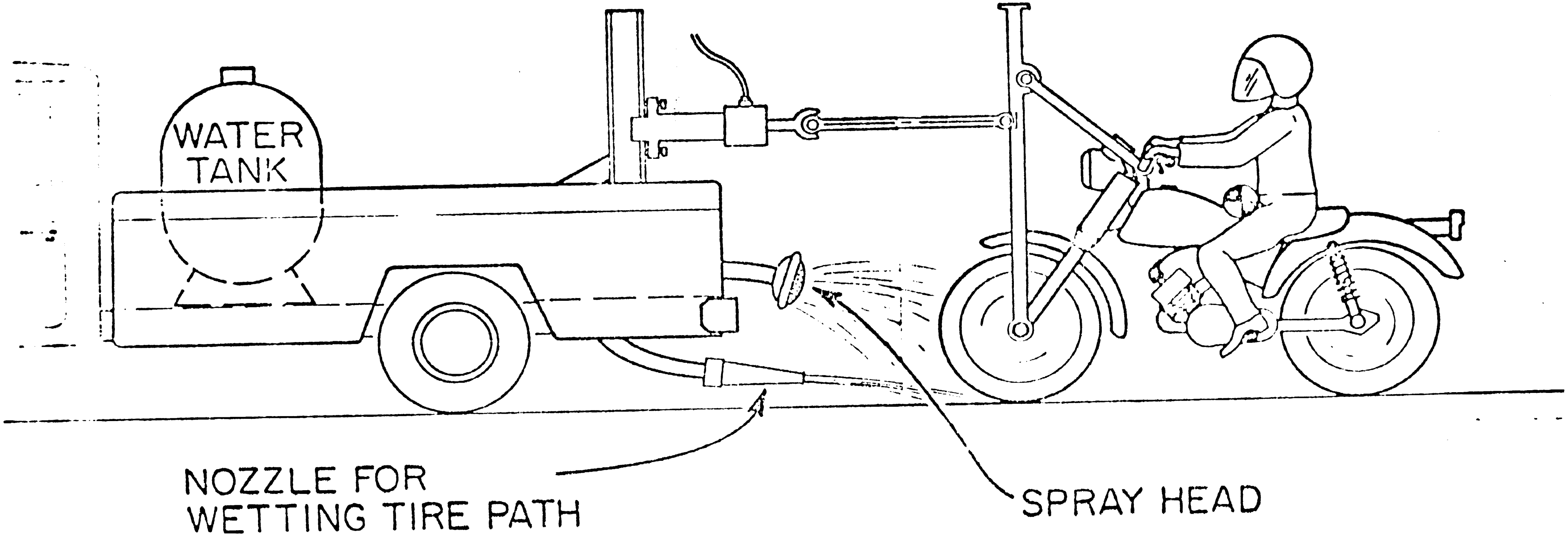


Figure 7. Tow system configuration for simulating wet weather riding condition.

brake's water exposure derives from drainage off of fenders following the centrifugal transfer of water picked up by the tires.

Water delivered by the elevated spray head is held constant throughout the conditioning process, providing an airborne flow similar to that which derives from both direct rain flow and traffic-generated mist.

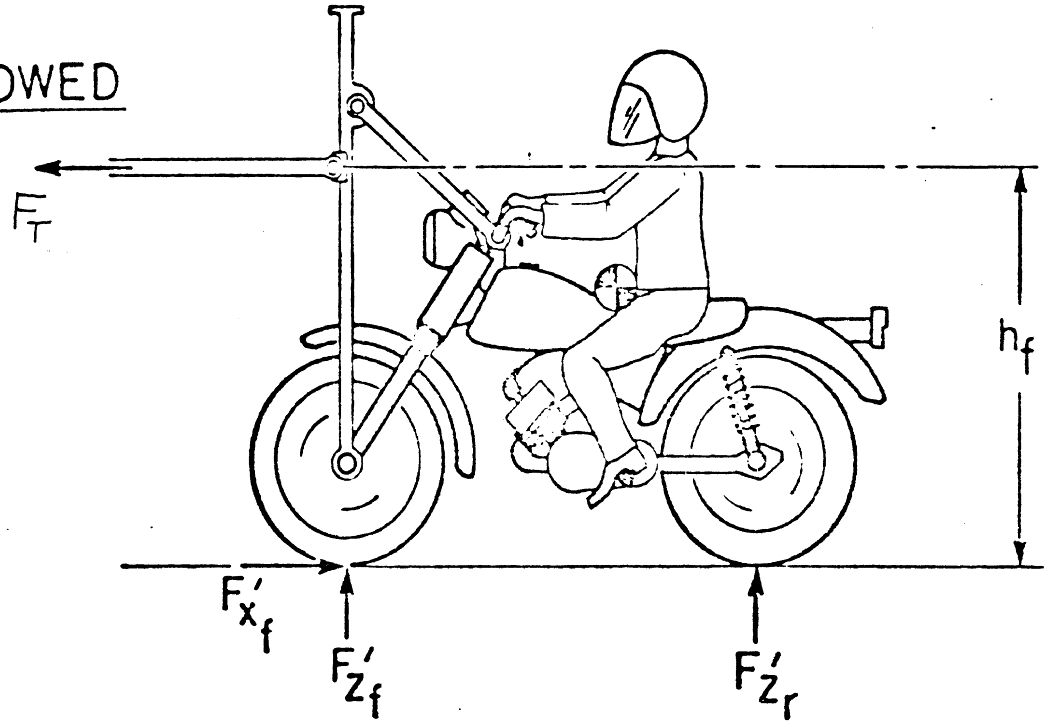
The dynamic wetting procedure is especially pertinent in the motorcycle case, it is reasoned, because of the exposed nature of motorcycle brake assemblies. On the other hand, the described technique avoids artificially "over exposing" motorcycle brakes by forcing water through zero-pressure seals, such as occurs in "immersion"-type wetting procedures.

The assessment of "wet brake" effectiveness involves a spot check of the control input force/tow force relationship at front and rear brake systems. The spot check occurs while the wetting activity is still in progress, thereby characterizing the influence of the wet environment as is relevant to braking in wet weather.

Effectiveness Test Procedure

The application of the tow-test concept to the characterization of braking capability limits requires that an analogy be established between the contrived tow experiment and the free-stopping process of the dual-braked motorcycle. Specifically, there is a need to establish the traction limits of front and rear tires under respective vertical load conditions such as would derive in a two-wheel-braked stop. As illustrated in Figure 8, this criterion implies that the towed motorcycle experience a forward transfer of vertical load in the front- and rear-only braking tests which is equivalent with that experienced by the hypothetical, dual-braked, free-stopping motorcycle.

TOWED



FREE-STOPPING

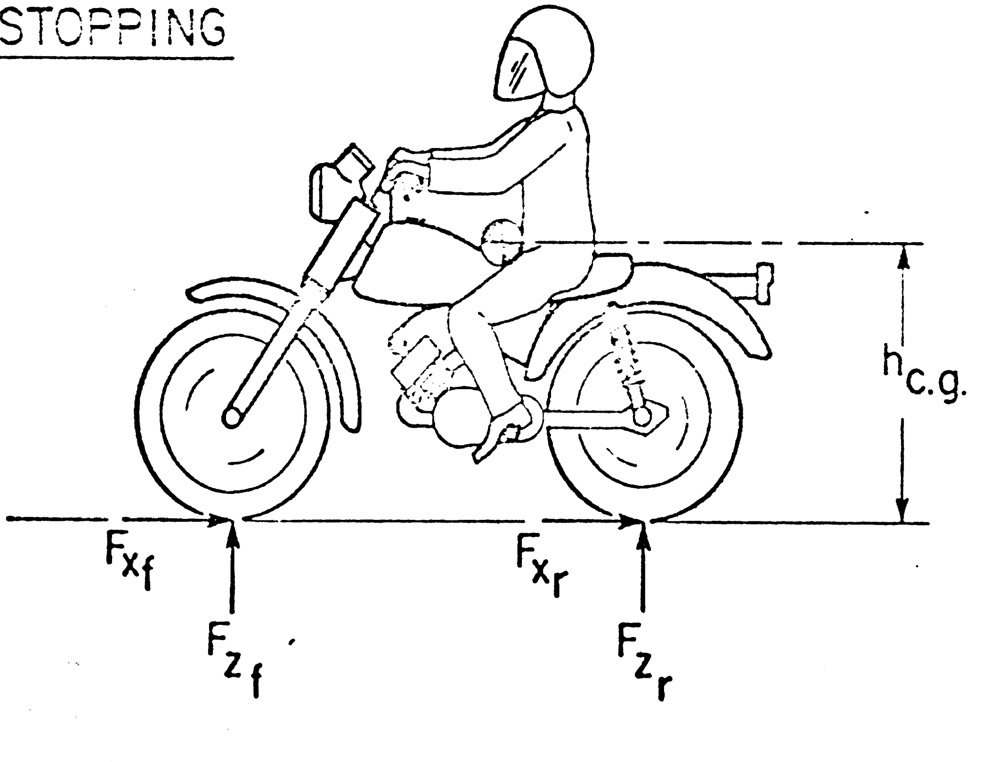


Figure 8. The towed motorcycle is equivalent to the free-stopping case when $F_{z'_f} = F_{z_f}$ and $F_{z'_r} = F_{z_r}$.

The key consideration, here, is that the traction limits of pneumatic tires are constrained by friction mechanisms which are inherently sensitive to the normal force which is imposed upon the tire. Beyond the first-order coulomb relationship, by which the normalized force, $\mu = F_x/F_z$, becomes useful, there generally exists a higher order, but not insignificant, influence of F_z on μ, itself. Thus, since each motorcycle's mass location and wheelbase determine its dynamic tire loading and, consequently, traction-limited braking capability, it is paramount that the towing test method accrue realistic tire loads during its traction-limited experiments.

It should be clear that a vehicle being towed at constant velocity will experience load transfers in proportion to

a) the braking forces which are generated at the tire-road interface, and

b) the height at which the tow force is applied.

Accordingly, for the towed, single-braked motorcycle in Figure 8 to experience load transfer equivalent to that of the free-stopping vehicle, it is necessary that the tow height, h_n, be adjusted to effect the needed pitch moment. Additionally, it should be apparent that distinct values of h_n will be found appropriate for front- and rear-wheel-only braking, viz., $h_n = h_f, h_r$.

Thus we have formulated a test procedure which permits determination of the braking limits of the total motorcycle by way of individual assessments of front and rear tire traction limits. The procedure involves a sequence of tow height selections, braking force measurements, and simple arithmetic calculations to yield a measure of total vehicle performance. The following constitutes a general outline of the effectiveness sequence:

1) The first trial value of tow attachment height, h_r, (greater than the c.g. height, h) is selected for use in the first rear-only braking test.

2) The rear brake actuator is applied in a ramp-type fashion, causing the rear tire to experience its traction peak, yielding a peak tow force measurement of F'_{x_r} (the "prime"-indicated variables such as F'_{x_r} indicate values deriving from the prevailing tow-test conditions).

3) The rear tire vertical load, F'_{z_r}, and the traction coefficient, μ'_r, are calculated as they prevailed during the previous test, per the relationships:

$$F'_{z_r} = W_r - \frac{h_r}{\ell} F'_{x_r} \tag{3}$$

and

$$\mu'_r = F'_{x_r}/F'_{z_r} \tag{4}$$

where W_r = static load on rear tire

ℓ = wheelbase

4) A value of tow attachment height, h_f, is selected for use in the first front-only braking test.

5) The front-only braking measurement is conducted, yielding a peak tow force value of F'_{x_f}.

6) F'_{z_f} and μ'_f are then determined in a fashion comparable to that employed in the rear-only process, per the relations:

$$F'_{z_f} = W_f + \frac{h_f}{\ell} F'_{x_f} \tag{5}$$

and

$$\mu'_f = F'_{x_f}/F'_{z_f} \tag{6}$$

7) The obtained values μ_f' and μ_r' are introduced, as the first approximations of front and rear traction coefficients, into the expressions for the front and rear tire loads, F_{z_f} and F_{z_r}, which would prevail on the dual-braked, free-stopping motorcycle (if it were caused to simultaneously accrue its front and rear tire traction limits on the same test surface) per the relations:

$$F_{x_f} = W_f + \frac{h(\mu_f' W_f + \mu_r' W_r)}{\ell + h(\mu_r' - \mu_f')} \qquad (7)$$

$$F_{z_r} = W_r - \frac{h(\mu_f' W_f + \mu_r' W_r)}{\ell + h(\mu_r' - \mu_f')} \qquad (8)$$

8) F_{z_f} is next examined in comparison with the value of load, F_{z_f}', actually obtained during the front-only tow test. Likewise, F_{z_r} is compared with F_{z_r}'. For an improved correlation between the reference (F_{z_n}) and actual (F_{z_n}') values, an iteration loop is established, returning to step (1) and selecting improved values for h_r and h_f. The new tow height selections are guided as follows:

- If F_{z_f}' was found to be higher than F_{z_f}, a lower value of h_f should be selected.
- If F_{z_r}' was found to be higher than F_{z_r}, a higher value of h_r should be selected.

In the actual implementation of this concept, to be discussed later, the iteration sequence is guided by a formula such that the field test operation is simple and efficient.

9) When F'_{z_f} and F'_{z_r} have been obtained to within a defined tolerance of F_{z_f} and F_{z_r}, respectively, the total motorcycle's limit braking capability is defined by the expression:

$$A_x = \frac{F'_{x_f}\left(\frac{F_{z_f}}{F'_{z_f}}\right) + F'_{x_r}\left(\frac{F_{z_r}}{F'_{z_r}}\right)}{W/g} \tag{9}$$

where A_x = limit longitudinal acceleration in units of ft/sec^2

W = total vehicle weight

g = 32.2 ft/sec^2

The overall procedure which has been described here is conceived as applying to both the pre- and post-burnish effectiveness tests even though we hypothesize no relationship between the burnishing process and the traction limits of installed tires. Rather, the effectiveness assessment prior to and following burnish is addressed toward those brake systems which are, ultimately, brake torque- rather than tire traction-limited and which are thus subject to change as a consequence of the burnish process. The need to characterize the maximum capability of torque-limited braking systems requires that the tow test with single-wheel braking be designed so as to accommodate the three torque-limited possibilities, viz.,

Case 1) both front and rear brake systems are torque-limited (as measured within the ergonomic limits on actuator forces)

Case 2) the front brake system is traction-limited and the rear is torque-limited

Case 3) the rear system is traction-limited and the front is torque-limited.

The basic sequence of the procedure for testing vehicles falling in these categories is as described before. Clearly, the vertical load prevailing on a torque-limited wheel is inconsequential. Nevertheless, implicit in the "torque-limited" conclusion is a vertical load condition at which the brake is incapable of wheel-locking.

The representativeness of the dynamic vertical load condition thus remains as a basic requirement of the method, even for torque-limited braking systems. The total acceleration measure for each of the three cases cited is obtained through modified versions of Equation (9) as given below:

for Case 1)
$$A_x = \frac{F'_{x_f} + F'_{x_r}}{W/g} \qquad (10)$$

for Case 2)
$$A_x = \frac{F'_{x_r} + F'_{x_f}\left[\dfrac{W_f \ell + hF'_{x_r}}{F'_{z_f}\,(\ell - \mu'_f h)}\right]}{W/g} \qquad (11)$$

for Case 3)
$$A_x = \frac{F'_{x_f} + F'_{x_r}\left[\dfrac{W_r \ell - hF'_{x_f}}{F'_{z_r}\,(\ell + \mu'_r h)}\right]}{W/g} \qquad (12)$$

where the bracketed expression represents (F_{z_r}/F'_{z_r}) with F_{z_r} deriving from a different form of Equation (8).

Thus the effectiveness test concept permits measurement of a motorcycle's braking limits whether these limits are determined by tire traction or overall brake torque constraints. The test procedure, while employing only single-wheel braking, results in a stopping distance measure identical to that which would be attained by a motorcycle whose front and rear braking limits were sustained simultaneously throughout the stop.

3.3 Test Procedure Employing the Unified Concept

The generalized concept of testing outlined in the previous section has been formalized into a detailed specification of test procedures, which are set forth below. It should be noted that this procedure was developed and refined during a separate test phase in this study. While this section serves to state the procedure in its basic form, specific application of the method to two selected motorcycles will be discussed in Section 3.4.

3.3.1 Test Procedures.

Vehicle Setup

The test motorcycle is to be outfitted with new tires and brake linings. The brake adjustments and tire inflations are to be according to the manufacturer's recommendations. The vehicle is to be connected to a towing system permitting application of a single, measurable towing force at a variable height above the ground. All tests of the vehicle are to be conducted with engine off and with transmission in neutral.

Brake Warming

If, within 1/2 minute prior to the initiation of any of the below-described test sequences, the temperature of the brake being tested is below 130°F, a warming procedure will be conducted. At a steady speed of 30 mph, the brake will be applied to yield a tow force, FT, equivalent to an acceleration level of 10 ft/sec^2. Thus, the respective front-only and rear-only steady tow force conditions, FT_f and FT_r, are as determined in Equations (13) and (14), with $A_x = 10/g$.

$$FT_f = A_x[W_f + \frac{h}{\ell} \cdot A_x \cdot W] \quad , \text{(front only)} \qquad (13)$$

and

$$FT_r = A_x[W_r - \frac{h}{\ell} \cdot A_x \cdot W] \quad , \text{(rear only)} \qquad (14)$$

where

A_x is the specified equivalent deceleration in g's

W_f is the static front wheel load

W_r is the static rear wheel load

h is the c.g. height

ℓ is wheelbase

W is the total weight

The brake application (for warming) can be continuously maintained for a maximum of 22 seconds or until a 130°F initial temperature is attained.

Pre-Burnish Effectiveness Test

Tests are to be conducted at a steady speed of 40 mph and, in a sequence of runs, are to be initiated only when the tested brake exhibits a temperature below 180°F.

The effectiveness test sequence is organized per the flow chart of Figure 9 and involves the following steps:

1) Start the sequence (either as a pre- or post-burnish test).
2) The tow height (at which the initial rear-only test is to be conducted) is placed at 60".
3) The force input to the rear actuator is applied at a rate which causes (a) either wheel lockup or (b) a 90-lb actuator force level to be obtained

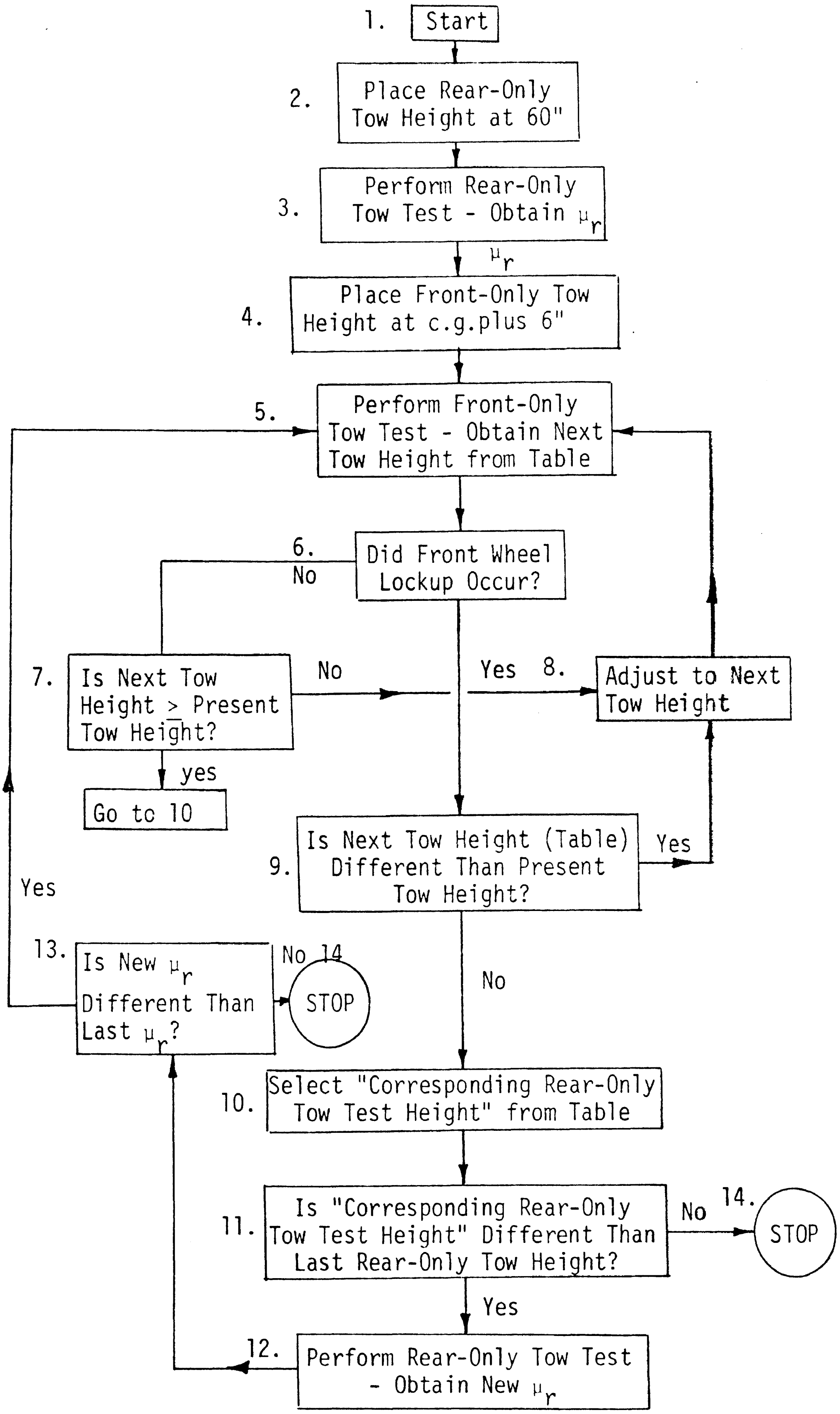


Figure 9. Effectiveness Test Flow Chart

between 2 and 5 seconds after initiating the brake application. The resulting peak tow-force reading is used to calculate the value of peak μ_r using Equation (15).

$$\mu_r = \frac{FT_R}{W_r - \frac{h_{tr}}{\ell} FT_R} \qquad (15)$$

where

FT_R is peak tow force value measured in rear-only test

W_r is the static rear wheel load

h_{tr} is the rear-only tow height

and ℓ is the wheelbase.

The calculated value of μ_r is used for selecting tow heights in subsequent front-only effectiveness tests according to Equation (16), viz.,

$$h_{i+1} = \frac{\ell \; (W_r \mu_r + FT_i)(\frac{h}{\ell + h \mu_r})}{FT_i} \qquad (16)$$

where

h_{i+1} is next value of tow height to be employed in front-only tests

FT_i is peak tow force attained in the previous (ith) brake application

h is the cycle/rider c.g. height

μ_r is the rear-only normalized force coefficient

[Note: Equation (16) has been computerized for tests conducted in this study providing a set of pre-calculated tables to guide tow height selection in the field. (See Section 3.4.2.) It is not generally expected that the iteration calculations will be done as a direct accompaniment to the test process itself.]

4) The tow height to be used in the first front-only test is placed at the position equal to:
(c.g. height + 6 inches).

5) The first front-only effectiveness test is conducted applying front actuator effort at a rate which causes (a) either wheel lockup or (b) a 55-lb actuator force, or (c) an actuator stroke limitation to be obtained within 2 to 5 seconds after initiating the brake application.

6) If, in Step 5, front-wheel lockup occurred, the procedure advances to Step 9. If, in Step 5, front-wheel lockup did not occur, the procedure advances to Step 7.

7) Solving Equation (16) using the value of FT just obtained in Step 5, a determination is made as to whether (a) the NEXT TOW HEIGHT (h_{i+1}) is <u>greater than or equal</u> to (± 1 inch) the tow height employed in Step 5, or (b) the NEXT TOW HEIGHT is <u>less than</u> the tow height employed in Step 5. If (a), then the sequence proceeds to Step 10. If (b), then the sequence proceeds to Step 8.

8) The value of NEXT TOW HEIGHT is then implemented by the adjustment of tow linkages. The sequence then proceeds with another front-only test as in Step 5.

9) If in Step 5 a wheel lockup did occur, a determination is made as to whether the NEXT TOW HEIGHT is (a) different from, or (b) the same as that just employed in the Step 5 test. If (a), then the sequence proceeds to Step 8; if (b), then the sequence proceeds to Step 10.

10) The value of CORRESPONDING REAR-ONLY TOW HEIGHT, h_r, is determined according to Equation (17) (or, again, using a tabulated solution of this equation to improve the efficiency of testing in the field).

$$h_r = h \left[1 + \frac{FT_i}{\mu_r \left(W_r - \frac{h_{i+1}}{\ell} FT_i \right)} \right] \tag{17}$$

11) A determination is made as to whether the value of CORRESPONDING REAR-ONLY TOW HEIGHT is (a) different from, or (b) the same as (± 1 inch) the last value of rear-only tow height which was employed. If (a), then the sequence proceeds to Step 12. If (b), then the sequence stops.

12) Upon selecting a new rear-only tow height, a new rear-only test is performed according to the procedure of Step 3. A new value of μ_r is calculated using Equation (15).

13) A determination is made as to whether the new value of μ_r, when rounded off to the nearest 0.05, (a) differs by more than (0.05) from the previous value of μ_r, or (b) is within (0.05) of the previous value of μ_r. If (a), then the sequence proceeds to Step 5. If (b), then the sequence stops.

14) When front and rear tow heights have converged to the values satisfying the iteration criteria, three repeat measurements are made of the rear-only and front-only effectiveness tests, using the final values of tow heights.

Burnish Procedure

The front brake will be burnished by attaining prescribed values of tow force using front-only brake applications over a sequence of 200 constant level applications. A tow force level equivalent to $A_x = 12/g$ (in the front-only Equation (13)) will be applied, at a constant test speed of 40 mph, for a duration of 4 seconds at each application. The tow force is to be applied at an elevation equal to the height of the mass center of the cycle/test-rider system. The braking interval will be either that distance needed to reduce brake temperature to 150°F or 1 mile, whichever occurs first. Following burnishing, brakes will be adjusted to manufacturers' specifications.

The rear brake will be burnished by a procedure identical to that described above, except that tow force level shall be as specified by Equation (14), with $A_x = 12/g$.

Post-Burnish Effectiveness

The basic effectiveness procedure described previously as the "pre-burnish" effectiveness procedure will be repeated here.

Thermal Capacity (Fade) Procedure

A thermal loading sequence will be conducted involving a baseline check followed by a series of high energy brake applications.

Baseline Check. At a constant speed of 30 mph, the front brake will be applied for a duration of 4 seconds, achieving a tow force equivalent to $A_x = 15/g$ in the front-only Equation (13). Three braking inputs shall be applied, each with an initial temperature between 130°F and 180°F. The same three-application sequence shall be conducted using the rear brake, and employing a tow force as specified by Equation (14) using $A_x = 15/g$.

Thermal Loading. A total of ten (10) brake applications using front-only braking will be applied at a constant speed of 30 mph, achieving a tow force value corresponding to $A_x = 15/g$ in Equation (13). The initial temperature before the first brake application shall be below 150°F. The constant tow force level shall be sustained for 6 seconds at each application. The interval between initiation of each brake application shall be 0.4 mile. The tow force is to be applied at the height of the mass center of the cycle/test-rider system for the fade test sequence. The above procedure shall be repeated using rear-only braking and a tow force value corresponding to $A_x = 15/g$ in Equation (14).

Wetted Performance

A water exposure sequence will be conducted providing (1) an initial baseline check of tow force/actuator effort gain, (2) a dynamic wetting procedure, and (3) a check of the tow force/actuator effort gain of the water-exposed brake system. All braking in this sequence is to be done with the tow force applied at the height of the cycle/rider mass center.

Baseline Check. At a constant speed of 30 mph, the front brake will be applied to achieve a tow force corresponding to $A_x = 10/g$ in Equation (13). The brake input will be sustained for 4 seconds. Three applications will be made, starting with an initial temperature below 150°F and, thence, using an interval of 0.5 mile between initiation of each subsequent application.

Three rear-only applications are then applied, according to the above-described procedure, but with the tow force value corresponding to $A_x = 10/g$ in Equation (14).

Water Exposure Sequence. At a constant test speed of 30 mph, a water exposure condition is commenced applying water to the pavement in the path of the motorcycle wheels equivalent to a 0.020-inch water depth and applying a continuous airborne spray representative of a 3 in/hr equivalent rainfall rate through two air-atomizing nozzles oriented to direct a horizontal flow at the wheel center heights along both sides of the test motorcycle. After sustaining the water exposure condition for 10 minutes, the tow force/actuator effort gains of front and rear brakes are rechecked according to the baseline check procedure, but now with the wetting procedure continuing during the brake applications (and foregoing the initial temperature constraint). The total sequence of three front and three rear actuations must be completed before a total of 20 minutes has elapsed since the start of the water exposure sequence.

3.3.2 Data Acquisition and Test Results Format. This section describes the data to be gathered during each of the test sequences defined in Section 3.2.1. The format for evaluating test results is also outlined. In the effectiveness, fade, and water exposure tests, results are obtained indicating vehicle performance quality; while the warming and burnish procedures produce no "results" per se, and will thus be documented only via sampling of test condition variables.

Pre-Burnish and Post-Burnish Effectiveness

The peak tow forces occurring for front-only and rear-only tow tests will be used to provide a measure of total vehicle performance in terms of vehicle stopping distance.

Peak tow force is simply defined as the maximum value of tow force which occurs during either a traction-limited or torque-limited single-wheel test without exceeding the specified actuator force limits (55 lb-front, 90 lb-rear). For those torque-limited tests in which the brake actuator force exceeds the specified limit, the tow force occurring at the time of the actuator force limit exceedance will be defined as the peak tow force.

The free-stopping distance, D, is calculated as

$$D = \frac{V_o^2}{(64.4)A_x} \tag{18}$$

where V_o is a free-stopping initial velocity (fps) and A_x is the equivalent total vehicle free-stopping deceleration which derives from the results of the front-only, rear-only, single-wheel tests (g's).

The value of A_x used in Equation (18) is then given by

$$A_x = \frac{FT_p + \mu_r \{W - [W_f + \frac{h_t}{\ell} FT_p]\}}{W} \tag{19}$$

where

FT_p is the peak tow force resulting from the front-only effectiveness tests

h_t is the convergent tow height obtained during the front-only effectiveness tests.

Thermal Capacity (Fade) Procedure

For the baseline check applications, the tow and actuator force values will be obtained by averaging the actuator force time histories over 2 seconds of the 6-second-duration input. An average of the three tow force values obtained using the front brake will then be ratioed to the average of the three front actuator force values yielding a gain value, viz.,

$$\text{Front Baseline Gain} = \frac{FT(\text{average of } 3)}{A_f(\text{average of } 3)}$$

Likewise, a gain value characterizing the rear baseline checks will be derived, viz.,

$$\text{Rear Baseline Gain} = \frac{FT(\text{average of } 3)}{A_r(\text{average of } 3)}$$

For each of the ten (10) thermal loading applications, two-second averages shall be obtained characterizing the respective tow force and actuator force conditions. Each pair of tow and front actuator force averages shall be ratioed to obtain faded system gain values for the front brake, viz.,

$$\text{Front Faded System Gain} = \frac{FT_n}{A_{f_n}} \frac{(\text{for the nth application})}{(\text{for the nth application})}$$

Likewise, faded system gain values for the rear brake shall be determined, viz.,

$$\text{Rear Faded System Gain} = \frac{FT_i}{A_{r_i}} \frac{(\text{for the ith application})}{(\text{for the ith application})}$$

Performance of the thermally loaded brake shall be determined by comparing the extreme values of faded system gains with the baseline check values and by comparing actuator forces with the ergonomic maximums.

Water Exposure Test

The respective tow and actuator force data will be operated upon to obtain gain values as defined for the case of the thermal capacity test series. Since the water exposure tests involve a three-application water-faded check, the water exposure sensitivity of the test motorcycle will be evaluated by comparing tow force/actuator force gains derived as the average of the three applications. Front- and rear-only applications will be treated independently, as was the case with the thermal fade results.

3.4 Rationale in Support of Procedural Details

The following discussion provides the rationale upon which the test procedures (detailed in Section 3.3) are founded or based.

3.4.1 Vehicle Setup. Although few would argue against the test motorcycle being outfitted with new brake linings and tires, the "engine off, transmission in neutral" requirement deserves a certain explanation. Clearly, for commonly marketed motorcycles, the engine plays no active role in brake system performance, except as an auxiliary rear-wheel retarder. During rear-wheel braking tests, the retardation imposed by a running, engaged engine merely poses a confounding influence; thus we choose to accept the traditional practice of disengaging the engine and transmission from the rear wheel. Further, in developmental tests, we have also removed the drive chain to avoid the inadvertent disturbance of a braking experiment which derives if the test rider happens to kick the shift lever out of its neutral position.

3.4.2 Brake Warming. The basic principle of brake warming employed in FMVSS 122 has been adopted since the need to establish an objective method of reaching initial brake temperatures prior to testing is recognized. However, the proposed tow-test procedure specifies a "1/2 minute" interval as the time prior to testing during which the initial temperature minimum must be met. This specification is favored over the 122 requirement of "0.2 mile" since, in our view, the cooling of a brake is more meaningfully controlled by a time rather than a distance constraint when it is impractical to specify a reference velocity.

The initial temperature minimum of 130°F (also specified by FMVSS 122) is adopted on the basis of certain observations concerning motorcycle brake systems. Although very little hard evidence is available, it appears that motorcycle brake systems do run much cooler than comparable systems on automobiles.

In the 122 test series conducted during this study, all cycles were observed to register brake temperatures of 150°F or less (except for the rear brake on the Harley-Davidson FXE-1200) as the equilibrium condition throughout the burnish procedure. In most cases, the distance traveled between burnish intervals was much less than one mile (the Honda CB 400F, for example, could only travel 0.2 mile between braking applications—before the hottest brake cooled to below 150°F). Thus the specification of an initial temperature equal to 130°F does seem to represent a reasonable condition for testing motorcycle brakes.

It is important that the initial required temperature not be set too high since the maintenance of a high minimum temperature constitutes a procedural nuisance. In conducting the effectiveness test procedure, for example, it is necessary to stop operations and adjust tow height frequently. If the required minimum temperature is somewhat high, there is a need to go through the warming procedure frequently, thereby increasing the time required to complete the test. Since all indications are that motorcycle brake systems are quite insensitive to lining temperatures in the 100° to 200°F range*, it seems appropriate and otherwise efficient to select a minimum temperature of 130°F.

The test conditions specified in the warming procedure (30 mph, 10 ft/sec^2 equivalent acceleration, and 22 sec. maximum duration) are derived from the existing 122 specifications for want of any other arbitrary guideline. Although the warming condition

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*We have noted, for example, that the four vehicles examined earlier during the 122 test series indicated no perceptible changes in brake performance over the temperature range 85° to 300°F.

requirement of FMVSS 122 seemed to represent a reasonable quantity of energy, the time rate of input of that energy was not specified. We have applied the same total amount of energy as the 122 method, but have compressed the energy input period to 22 seconds (as is, of course, straightforward in the towing technique). We justify the compressed input period on the grounds that the warming procedure has no other purpose but "to warm." Since we find no evidence that the energy input rate affects the character of an initial temperature condition (given that a substantial "penetration" of that energy into the rubbing elements is expected), a compressed warming technique is accordingly adopted as an efficient and effective means to attain the specified initial temperature.

3.4.3 Effectiveness Tests (Pre- and Post-Burnish). At first glance, the single-wheel effectiveness test procedure may appear as a complicated exercise for obtaining a measure of motorcycle braking effectiveness. In comparison to FMVSS 122 practice, the proposed procedure does involve greater complexity, but only to the degree necessary to eliminate the lack of objectivity inherent in the present test procedure.

Given that single-wheel testing provides the objectivity lacking in the present effectiveness test procedure, it is pertinent to consider those methodological features which are required to assure an equivalence between the single-wheel test results and the braking performance capability of the free-stopping motorcycle. Clearly, as presented earlier, a key requirement is that single-wheel tests should be conducted at the same vertical wheel loads which would result from the dual-braked, free-stopping motorcycle. As was discussed, this criterion implies that the towed motorcycle experience a forward transfer of vertical load in the front- and rear-only braking tests which is equivalent with that experienced by the dual-braked, free-stopping motorcycle. As was shown in

Section 3.3, the proper tire load conditions are achieved by towing the motorcycle with a tow bar located at the proper height for front- and rear-wheel-only braking.

The determination of these proper tow heights is therefore a central focus of the single-wheel effectiveness tests. Fortunately, a simple analysis of the fore-aft load transfer experienced by the free-stopping bike provides the basis for developing a mechanized procedure of selecting tow height which assures an efficient convergence to the "correct" value of tow height in the field.

This iterative procedure, deriving from the analysis presented in Appendix E, is embodied in Equations (16) and (17) and would typically be expanded to assist field testing through computation of a set of tables. It should be recognized that each step in the iterative procedure is contained within an organized decision and action process which has a number of steps. Each step involves merely a yes/no decision, a tow-height adjustment, or a single brake application. The accumulation of these steps in an effectiveness test series does not, in our view, add up to a large undertaking.

Additional comments are in order concerning other features of the effectiveness test procedure. In particular, the upper limit on the initial temperature allowable prior to each brake application (viz., 180°) was selected in the light of the observation that:

a) motorcycle brakes are quite insensitive to temperature in the range 100° to 200°F, and

b) test efficiency is increased when a higher value of initial temperature is permitted.

In addition, the decision to repeat the effectiveness tests three times at the final tow heights was based upon limited observations of the repeatability exhibited in the tests performed on the two motorcycles to which the method was applied. Note that a three-run repeat is also employed in baseline checks prior to the fade and water exposure tests.

3.4.4 Burnish Procedure. A major finding deriving from the FMVSS 122 test series was the discovery that the burnish procedure specified in the standard does not appear to provide an adequate level of "working" to the brakes. This observation was based upon the equilibrium temperatures and the percentage contact across the lining area attained during burnish rather than upon a perception concerning the achievement of an equilibrium condition of brake torque gain. Indeed, we know of no sources of data indicating typical transients in motorcycle brake torque effectiveness which accrue either from experimental burnishing or from the burnish experience of normal usage. Thus it was determined that for the purposes of the demonstration test program, a burnish procedure more severe than that employed in FMVSS 122 was desirable simply on the strength of evidence that the 122 method yields low temperatures and incomplete lining contact.

A series of developmental trials were conducted with the Kawasaki F9C, seeking a tow-test burnish procedure which constituted adequate conditioning of the brakes. Burnish sequences were conducted using the conditions described in the following table:

	Speed (mph)	Acceleration Equivalent (ft/sec^2)	Tow Force Duration (sec)	Braking Interval (mi)	Energy* Per Application (ft-lbs)	Equilibrium Temperature (°F)
FMVSS (122)	30	12	Complete Stop	1.0	7680	----
Tow Test Trials	30	12	2.0	1.0	8360	109
	30	12	3.0	1.0	12540	117
	30	12	5.0	1.0	20900	168
	40	12	3.0	1.0	16700	143
	40	12	4.0	1.0	22300	170
	40	12	5.0	1.0	27900	207

*Note that the "energy" descriptor is determined by the relationship:

$$\text{Energy} = (\text{average test speed}) \times (\text{tow force duration}) \times \left(\frac{\text{equiv. } A_x}{g}\right) \times W$$

expressed in units of ft-lbs.

These equilibrium temperature findings led to the 40 mph, 12 ft/sec^2, and 4 seconds duration condition being selected for use in the formal description of the procedure and in the demonstration test program.

Clearly, the independent burnish of front and rear brakes constitutes a basic characteristic of the tow-test method. Further, the determination of the tow forces to be used in the burnish sequence as per Equations (13) and (14) (see Section 3.3) assures a clean normalization of braking input level to account for the manner in which front and rear braking effort would be (ideally) distributed in service.

It should also be pointed out that the total number of brake applications for burnishing purposes, viz., 200, has been retained from the 122 procedure. This specification, together with the increased energy level requirement, clearly assures that the severity of the burnish procedure is upgraded with respect to that required by FMVSS 122. Finally, the setting of the tow attachment at the height of the cycle/rider c.g. merely serves to assure that wheel lockup will not occur during these relatively mild applications of brake torque.

3.4.5 Thermal Capacity (Fade) Procedure. Before discussing the rationale behind the fade procedure specified in Section 3.3, it is first pertinent to review certain considerations which led to discarding a conceptual alternative which was originally expected to form the basis for the selected method. This alternative involved the design of a thermal loading experiment which would be analogous to a mountain descent scenario. By this scenario, a "fade" test would be configured to simulate the continuous energy absorption involved in a mountain descent on the proposition that such a loading history constitutes the most severe braking condition (as has been generally established for passenger cars [1] and commercial vehicles [2]). The mountain-descent concept was found to be faulty when it was observed that the typical motorcycle would not, in fact, experience an excessive thermal loading as a consequence of the sustained retardation required in descending steep downgrades, such as are found in the U.S.

By way of explanation, consider that the travel of a motorcycle at steady speed down a mountain incline is determined by a balance of braking, gravity, and aerodynamic drag forces (neglecting engine retardation and rolling losses), as defined by the equation

$$F_B = W \sin \theta - CV^2$$

where

F_B = total braking force

W = vehicle weight

θ = roadway inclination

V = vehicle speed

C = aerodynamic constant ($C = 1/2\, \rho\, C_d A$

where ρ = air density
C_d = drag coefficient
A = projected frontal area of cycle and rider)

In the absence of braking, it can be shown that the coasting motorcycle will achieve a steady terminal velocity of:

$$V_t = \sqrt{\frac{W \sin \theta}{C}}$$

For a typical motorcycle and rider weighing 550 lbs (with C_d = 1.0), the terminal velocity on a 10% grade would be about 68 ft/sec. Thus a typical motorcycle can descend a 10% grade at a steady 46 mph with no braking retardation required at all.

Consider, now, the steady descent velocity at which the maximum rate of energy absorption would be required. We have that

$$\text{Brake Energy Rate} = F_b V = WV \sin\theta - CV^3$$

On differentiating to determine the velocity requiring maximum energy absorption, we obtain

$$\frac{d(\text{energy rate})}{dV} = W \sin\theta \; 3CV^2$$

or

$$V = \sqrt{\frac{W \sin\theta}{3C}}$$

Thus we see that the maximum energy absorption rate is obtained on a 10% grade at a steady speed of approximately 27 mph. At that velocity, the retardation force required for a 550-lb cycle and rider would be about 36 lbs. This sustained retardation would impose a braking energy rate of 1420 ft-lbs/sec. In contrast, the energy rate afforded by the FMVSS 122 fade procedure (if averaged over the time associated with all 10 stops) is in the vicinity of 2200 ft-lbs/sec. Thus, since the mountain-descending motorcycle must travel at unreasonably slow speeds to experience substantial rates of retardation energy input and since even those rates appear low in comparison with other severe usage conditions, the mountain descent scenario was discarded as the basis for a fade test procedure.

Implicit in the foregoing conclusion is a conviction that the fade sequence imposed by FMVSS 122 constitutes a loading sequence of reasonable severity. To reach this position one must expand his judgments of "reasonableness" to encompass such recreational motorcycling tactics as are apparently practiced by a not-insignificant portion of the motorcycle-riding population. By such scenarios, one envisions a rider who "blazes" through an urban area on a non-limited-access highway, applying 15 ft/sec^2 braking at signalized intersections, every 0.4 mile for ten stoplights in a row. Regardless of the palatability of such "literal" interpretations of the 122 fade sequence, it was determined that the overall energy experience was not out of order nor were the individual energy rates unreasonable. Further, since the four motorcycles tested in the 122 test series showed virtually no loss in braking capability as a consequence of this apparently conservative level of energy input, it would seem that the 122 fade sequence exacts little price in confirming a more than adequate level of thermal capacity.

The thermal capacity procedure outlined in Section 3.3 requires a set of three baseline check applications, but does not include a "recovery" sequence. The observation deriving from the results of numerous developmental tests and from the implications of the 122 test results is that the recovery procedure provides no valuable measure beyond that which can be obtained within the thermal loading sequence, itself. The principal argument is based upon limited data indicating that the motorcycle brake system generally improves in torque capability, if anything, as the system "recovers." Thus if the retention of brake torque capacity during the thermal loading sequence is thought to be a matter of concern, the procedure can obtain the relevant performance measure without resorting to a recovery braking phase. Additionally, the quality of the tow-test fade procedure appears sufficiently good from a repeatability point of view that the data gathered during the 10-application loading sequence can be used to provide a satisfactory performance measure.

Regarding the conditions prescribed for each "fade" application in the tow-test procedure, it should be noted that the specification of a 30-mph, 15 ft/sec^2, 6-second-duration braking input every 0.4 mile provides an energy input, at constant velocity, which is equal to that absorbed by a free-stopping motorcycle which brakes from the 60-mph velocity specified in FMVSS 122.

As a final consideration in defining a fade test procedure, there was a concern that certain front-torque-limited motorcycles might "pass" an effectiveness test but still not possess a sufficient braking capability on the front wheels to be able to conduct the 15 ft/sec^2 equivalent acceleration inputs required for the fade test. To explore that possibility, one must anticipate the front-wheel effectiveness "requirement" of the tow-test method.

Given the 122 stopping distance requirement for a full-system performance equal to 185 feet (equivalent to a 21 ft/sec^2 deceleration), we can compute the front wheel effectiveness required to attain that level of full-system performance. Let us assume, however, a full-system deceleration performance of 24 ft/sec^2 (.745 g's), since the tow-test method yields an "ultimate capability" which is free of the inefficiencies deriving from the rider's modulation of brake effort. If we then assume that the rear braking system on the typical motorcycle can accrue a brake force equal to the tire's peak traction limit, we can solve for the minimum remaining share of the braking capability which must be borne by the front brake. Thus, we can write that:

$$\frac{A_x}{g} = \frac{\mu F_{z_r} + CF_{z_f}}{W}$$

$$= \frac{\mu W\left[\dfrac{a - (A_x/g)h}{a+b}\right] + CW\left[\dfrac{b + (A_x/g)h}{a+b}\right]}{W}$$

where

μ = rear tire normalized traction peak

C = fractional front brake utilization of front tire vertical load

W = cycle/rider weight

On substituting representative numbers for the location of the center of mass, viz.,

$$\frac{a}{a+b} = .60 , \frac{b}{a+b} = .40 , \frac{h}{a+b} = .50$$

we have that,

$$\mu(.228) + C(.772) = A_x/g = .745 \text{ g's}$$

If $\mu = 1.0$ (as seems reasonable on dry pavement), then C must be at least = .67. Thus, to "pass" an effectiveness test requiring a .745 g deceleration, the (typical) front brake must provide a braking force of at least:

$$F_f = (.67)(.772)W = \underline{.517\ W}$$

This result can be contrasted with the front braking force needed to conduct the 15 ft/sec^2 condition required by the fade test. We merely solve Equation (15) from Section 3.3, using identical values for the parameters defining the c.g. location, and find that the F_f (required in the fade procedure) = $\underline{.289\ W}$. Thus, it is seen that the suggested effectiveness requirement serves to assure a sufficient level of front braking capability that the 15 ft/sec^2 test condition of the fade procedure can always be attained.

3.4.6 Wetted Brake Performance. The water exposure procedure is intended to provide a dynamic wetting condition similar to that such as may prevail while riding in a heavy rainfall. Water is delivered both to the pavement and via an airborne spray so as to account for the two basic paths of water impingement on brake assemblies (as was discussed in Section 3.2).

A baseline check of tow force/actuator force gains serves as a "bench mark" against which to evaluate the influence of water exposure. It should be recognized, however, that, until certain research is done, we have no firm basis for interpreting the significance of gain changes. Within the current state of knowledge, we can only place a certain confidence in the reasonableness of the ergonomic force limits, since there is no known source of data evaluating the significance of actuator effort gain (or changes thereof).

The water exposure experiment is designed to permit the measurement of "water-faded" gains while the wetting procedure is still in progress. Thus it has been specified that after 10 minutes of continuous water exposure, the rechecking of front and rear gains are initiated, and must be completed before another 10 minutes has elapsed. Clearly, the procedure has been limited to a duration compatible with reasonable limitations in stored water volume.

3.5 Demonstration of the Unified Test Concept

The demonstration tow tests were conducted using the Kawasaki and Harley-Davidson motorcycles described previously. The results of those tests are summarized below, while detailed data are presented in Appendix B. Less than two days were required for testing each motorcycle per the tow-test procedure, with the burnish sequence occupying nearly half of that time. Overall, the test procedure was found to be straightforward and practicable as a field test technique.

Two modifications were made to the test procedure during testing—one involving the installation of an additional hardware item to assure an accurate counterbalancing of the extraneous loads imposed by the towing constraint linkages, and the second involving an alteration of the effectiveness calculations used during the iterative test sequence. Both of these modifications were introduced during the testing of the first motorcycle and are discussed completely in Appendix B.

3.5.1 Tow-Test System. The basic layout of the tow-test system developed in this project is shown in the photos of Figures 10 through 16. A pickup truck provided the towing and mobile support services to the test motorcycle which is firmly constrained through an attaching linkage. By means of certain "tailored" adaptors, the test motorcycle was fastened to a standardized set of links. A "rider" is seated upon the cycle for purposes of loading the cycle and applying prescribed inputs to the brake control elements. During test operations, the towing vehicle is occupied by a test engineer who communicates with the rider via a wired headset. The test engineer also controls the synchronizing of test sequences with the data acquisition activity.

The photos of Figures 10-12 show the overall view of the test system. Figure 13 presents a view from the test rider's position. A closeup of the tow force meter is shown in Figure 14. Figure 15 shows a side view of the front wheel assembly/linkages and tow force transducer. The foot pedal force transducer is shown in Figure 16.

Various details of the tow-test system hardware design and instrumentation are discussed in Appendix C.

3.5.2 Test Motorcycle Preparation.

Prior to conducting the test procedure itself, various preparations are required. These preparations include measuring the mass center location, calculating certain tow forces and tow heights to be used during each stage of the procedure, and fabricating and installing certain hardware items.

Parameter Measurements

The motorcycle (and rider) parameters required by the method are (1) longitudinal center-of-gravity location, (2) center-of-gravity height, and (3) total weight. Each of these parameters are obtained by conducting simple lifting force measurements at

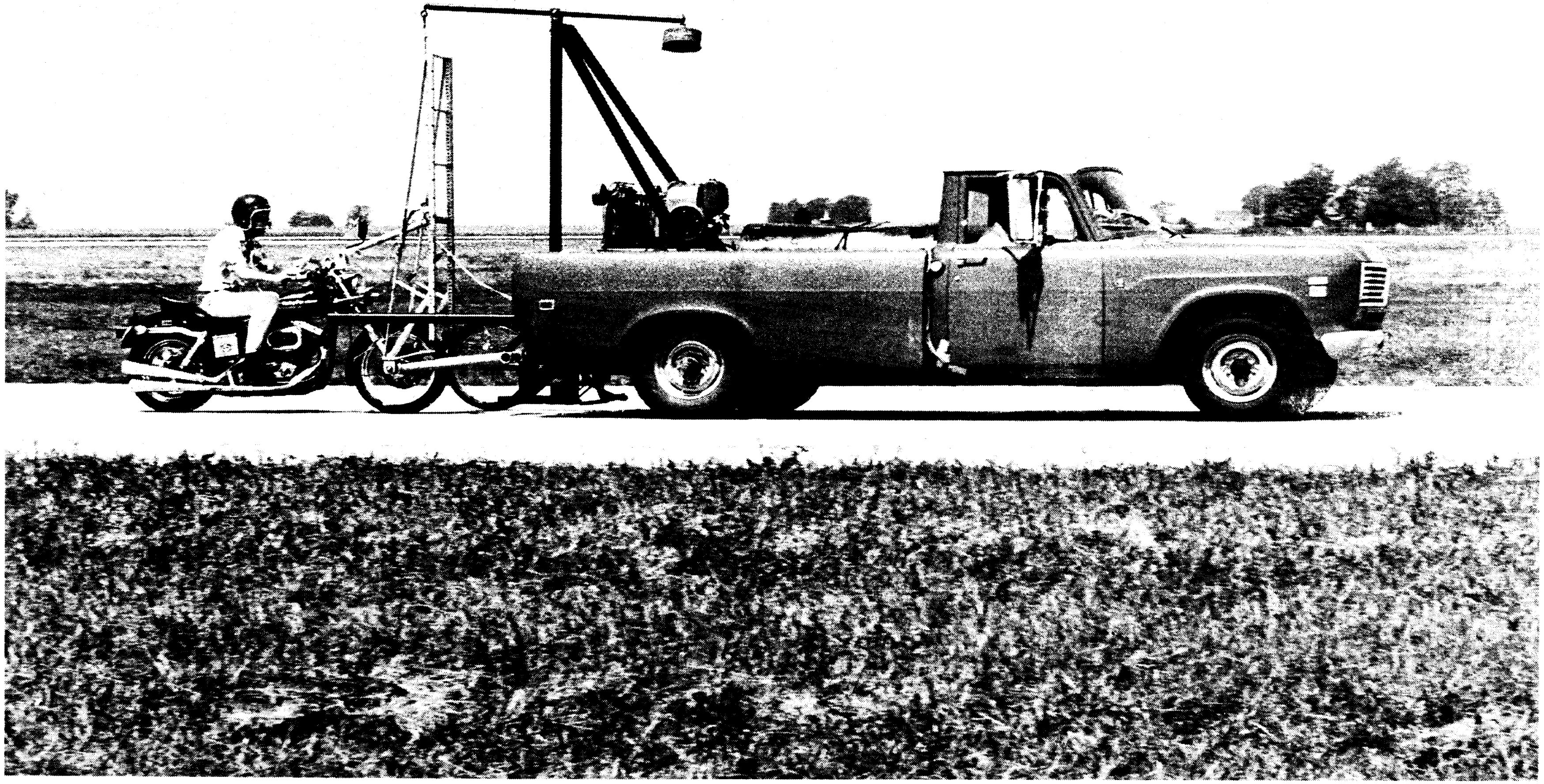

Figure 10. Tow-test apparatus employed during demonstration test program.

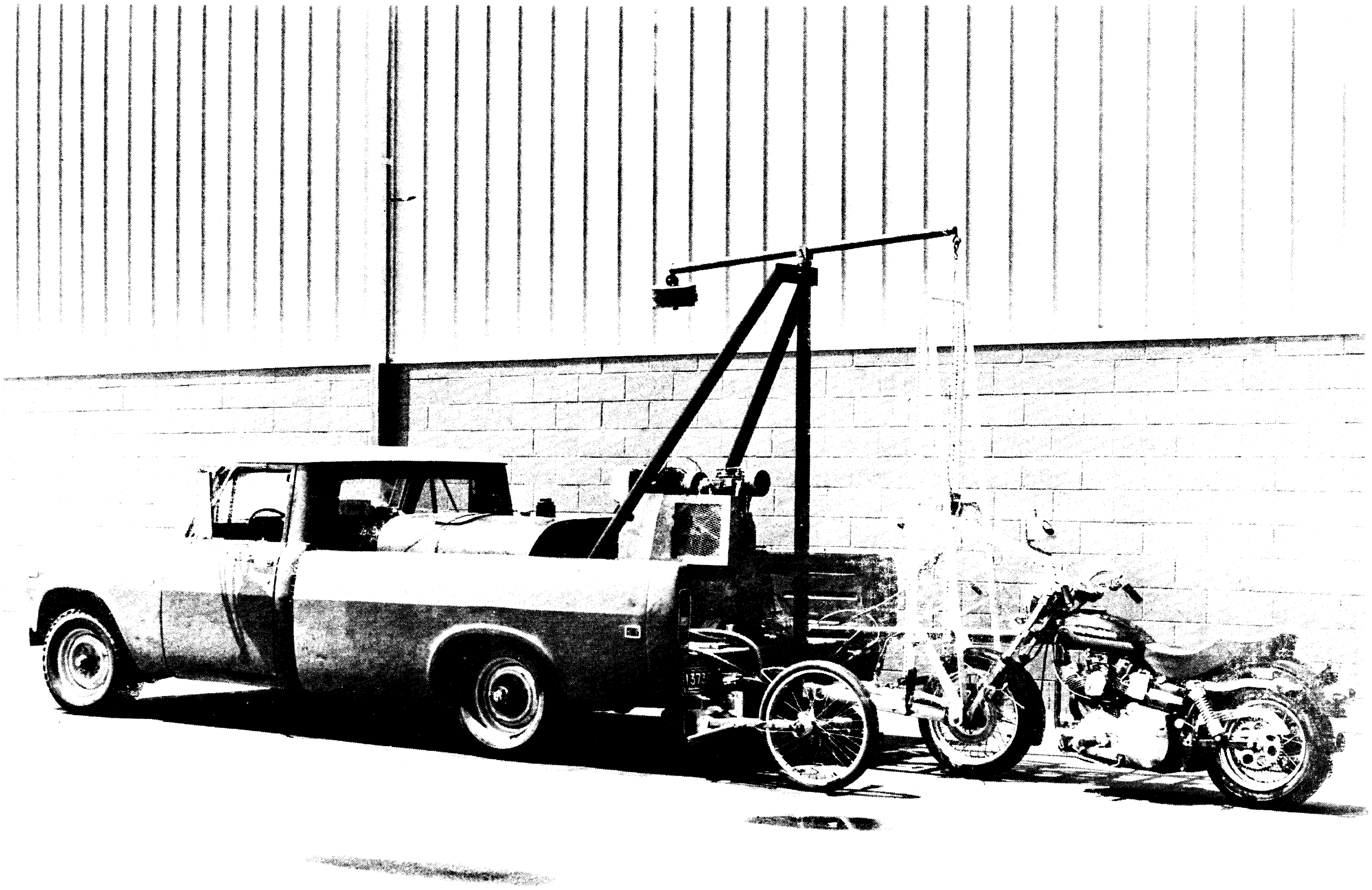

Figure 11. Overall view—tow vehicle carrying water tank, air compressor, tow attachment tower with counterbalancing weight, and fifth wheel.

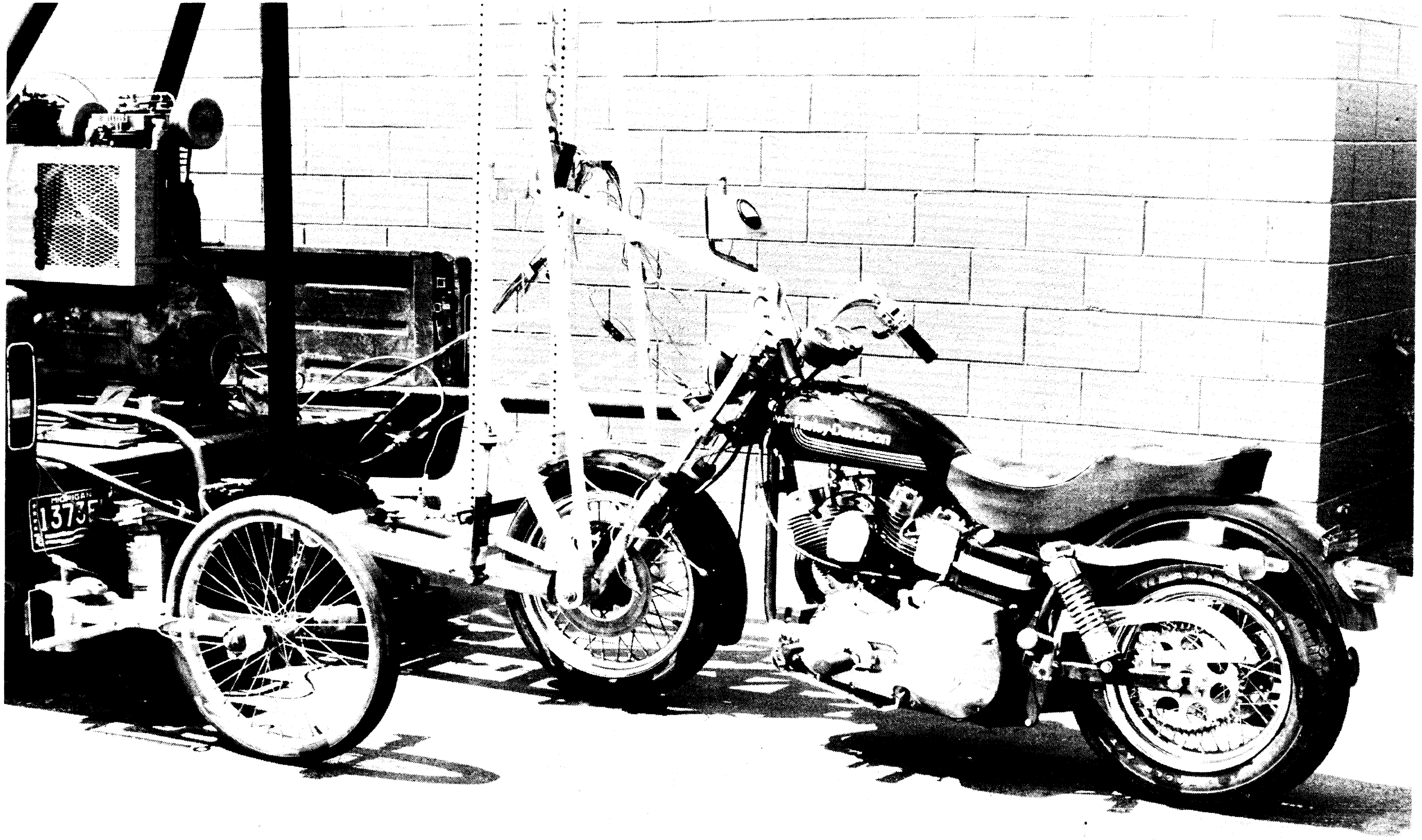

Figure 12. General tow linkage attachment to Harley-Davidson FXE-1200.

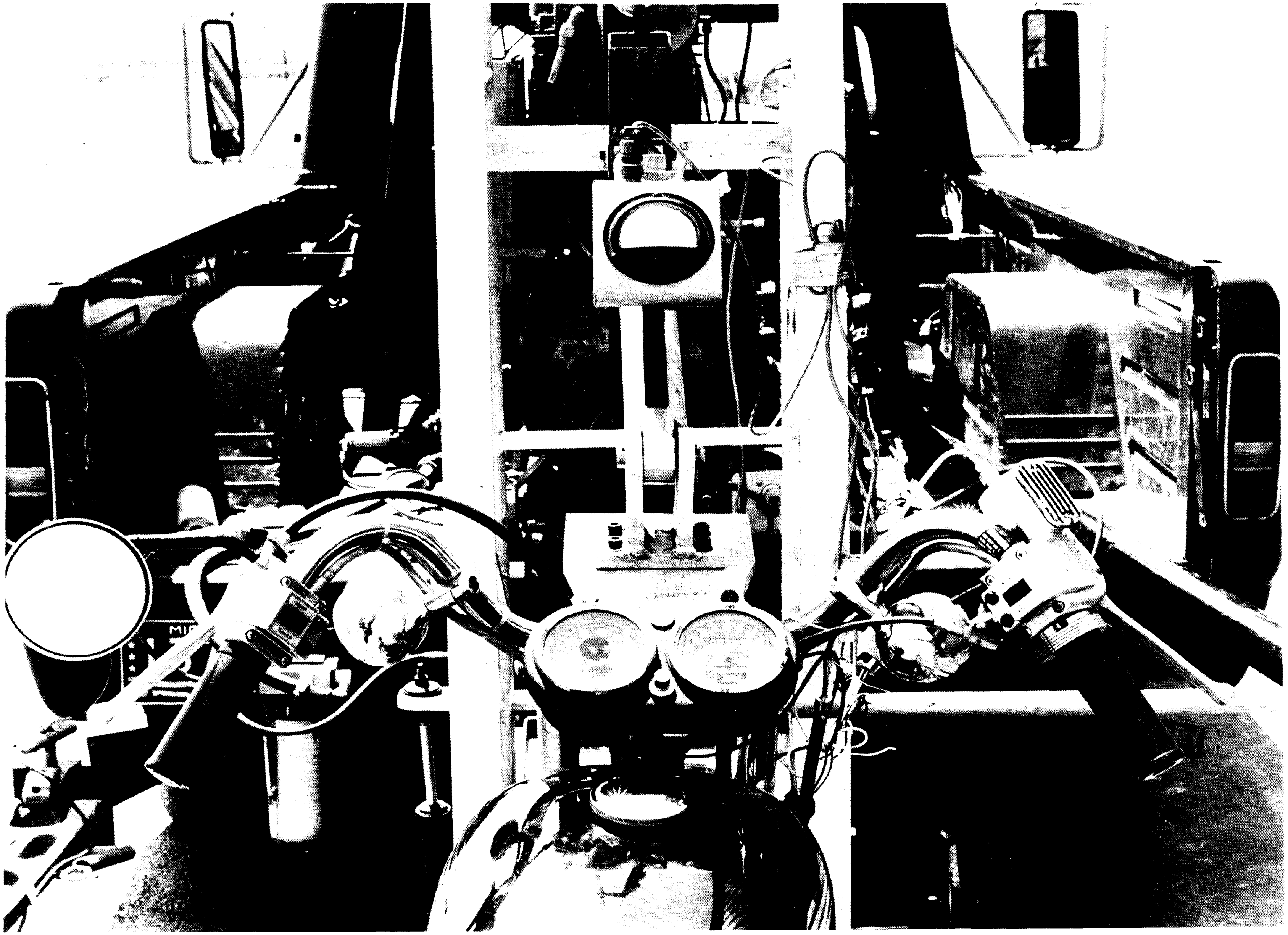

Figure 13. Test rider's view.

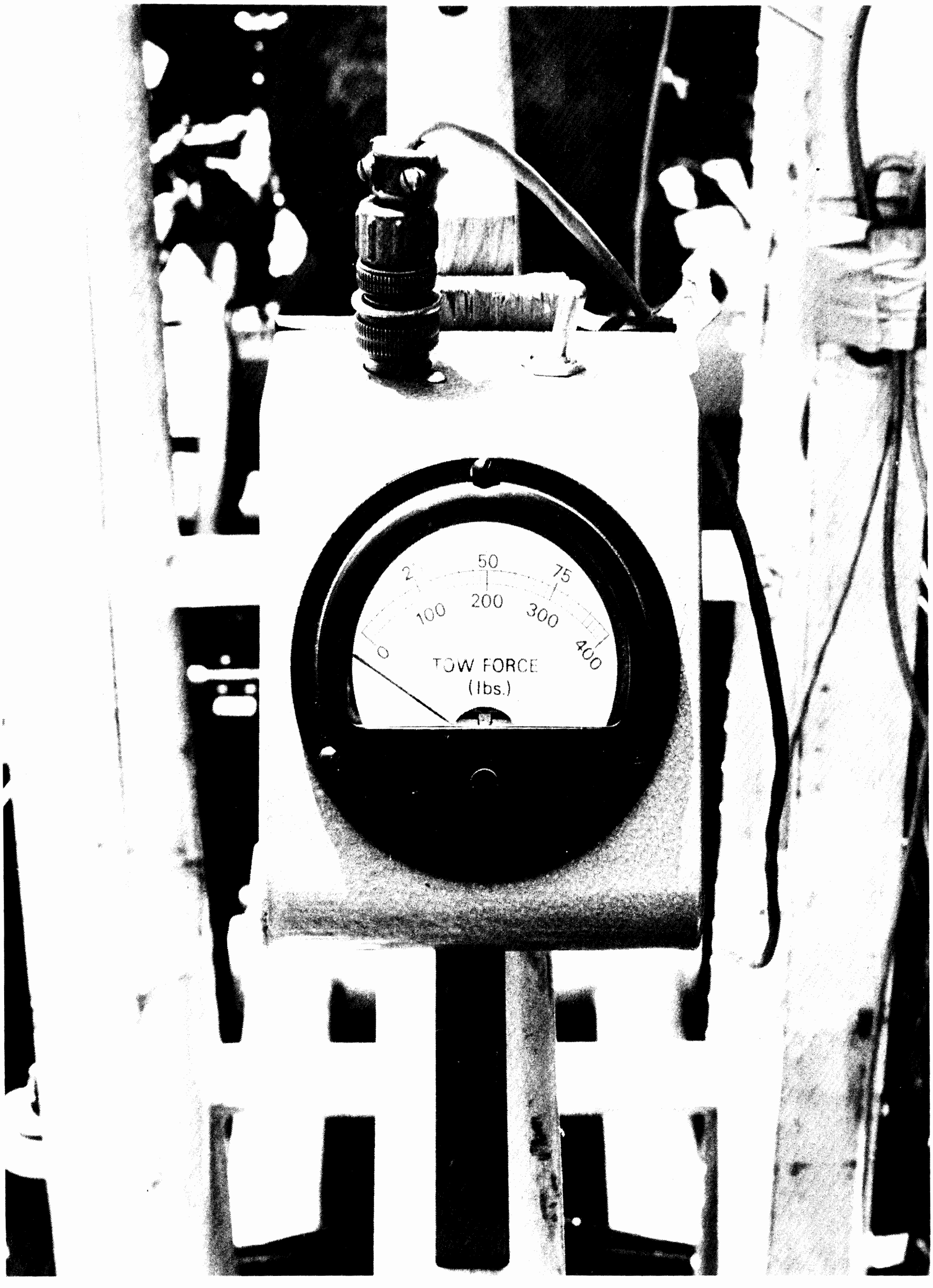

Figure 14. Tow force meter located directly in rider's view.

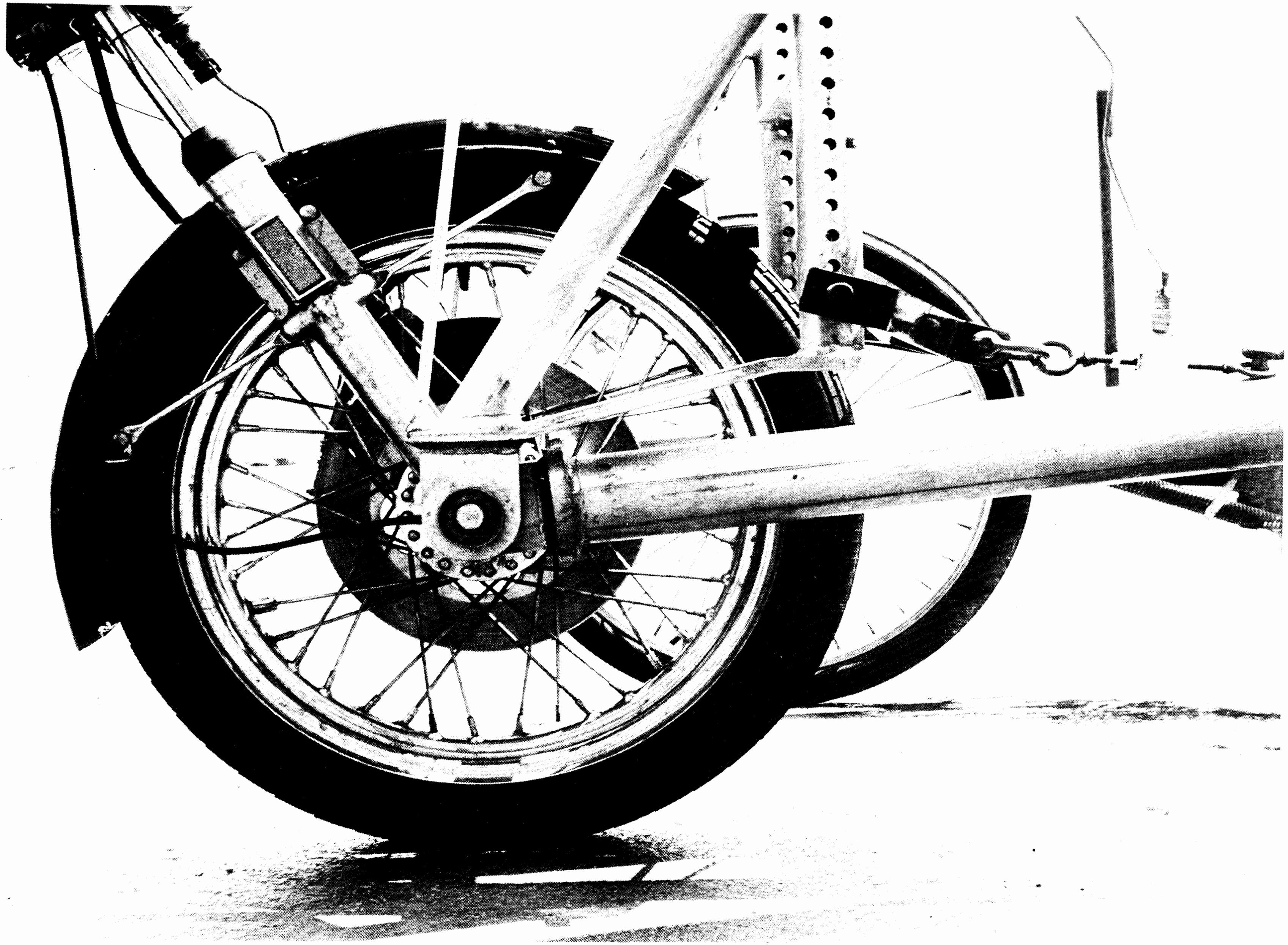

Figure 15. Tow linkage attachment on front wheel of Harley-Davidson FXE-1200 employing replacement front axle pin.

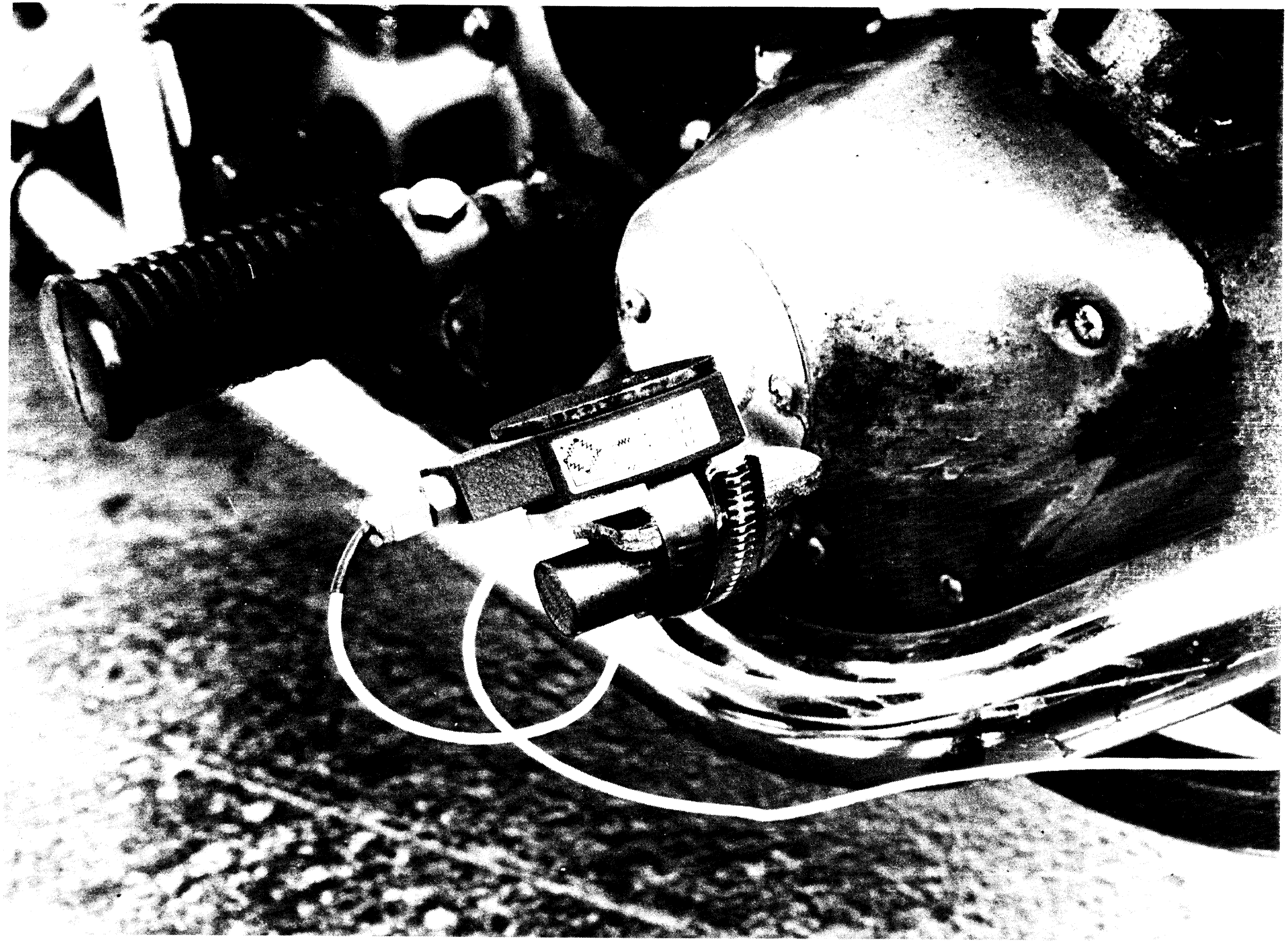

Figure 16. Pedal force transducer installed on Harley-Davidson FXE-1200.

the front and rear wheels. The c.g. height is calculated from front (or rear) lifting force measurements of the bike and rider inclined at varying angles. The parameter measurements for the Kawasaki F9C-350 and Harley-Davidson FXE-1200 test motorcycles using such a technique are shown in Table 4.

Calculations Required for the Test Procedure

During different portions of the test procedure (warm-up, burnish, fade, water recovery) specific deceleration levels* are prescribed. Each of these different deceleration levels is represented in the constant velocity tow-test procedure by an equivalent tow force. For example, a 0.40 g vehicle deceleration specification would be represented by an 80-lb tow force in a single-wheel test for which the respective dynamic wheel load is calculated to be 200 lb. Since each motorcycle is characterized by its particular value of weight and location of c.g., the need exists to calculate tow forces for each test motorcycle corresponding to the different deceleration levels specified in the test procedure. For single-wheel tests, the calculations relating equivalent tow force, FT, and specified deceleration are given by the generalized equations shown previously and provided again here for convenience, namely,

$$FT_f = A_x[W_f + \frac{h}{\ell} \cdot A_x \cdot W] \quad , \text{(front only)} \qquad (13)$$

and

$$FT_r = A_x[W_r - \frac{h}{\ell} \cdot A_x \cdot W] \quad , \text{(rear only)} \qquad (14)$$

---

*It should be noted that "deceleration level" was chosen as a braking level specification, despite the fact that the tow-test method involves only constant velocity experiments. This choice stems from a desire to permit a ready interpretation of tow-test braking levels by analogy to the more traditional stopping test procedures.

Table 4. Kawasaki and Harley-Davidson Parameter Measurements

	Kawasaki	Harley-Davidson
Wheelbase, (ℓ)	55.5"	63.3"
Front Wheel - c.g. Distance, (a)	35.0"	38.3"
Rear Wheel - c.g. Distance, (b)	20.5"	25.0"
c.g. Height Above Ground (with 165# Rider), (h)	27.0"	19.2"
Total Weight (with Rider), (W)	465 lb.	760 lb.
Static Front Wheel Load, (W_f)	172 lb.	300 lb.
Static Rear Wheel Load (W_r)	293 lb.	460 lb.

Tow Forces to be Employed in the Brake-Warming Procedure

The two general equations for front-only and rear-only tow forces (as given above) plus the specified warm-up deceleration of 10 ft/sec^2 (.31 g's), yield the warm-up tow forces for any bike as:

$$FT_{f_W} = (.31)\ [W_f + \frac{h}{\ell} \cdot (.31)W] \quad , \quad \text{(front only)}$$

$$FT_{r_W} = (.31)\ [W_r - \frac{h}{\ell} \cdot (.31)W] \quad , \quad \text{(rear only)}$$

On inserting the parameter values applicable to the Kawasaki and Harley-Davidson, the following tow forces for warm-up are obtained:

	Kawasaki	Harley-Davidson
(Front only)	75 lb.	115 lb.
(Rear only)	69 lb.	121 lb.

Burnish Tow Forces

For the specified burnish deceleration of 12 ft/sec^2 (.37 g's), Equations (13) and (14) reduce to

$$FT_{f_B} = (.37)\ [W_f + \frac{h}{\ell} (.37) \cdot W] \quad , \quad \text{(front only)}$$

$$FT_{r_B} = (.37)\ [W_r - \frac{h}{\ell} (.37) \cdot W] \quad , \quad \text{(rear only)}$$

which, in turn, yield the following tow forces for burnishing the brakes of the Kawasaki and Harley-Davidson, respectively:

	Kawasaki	Harley-Davidson
(Front only)	95 lb.	142 lb.
(Rear only)	78 lb.	139 lb.

The tow forces needed to execute the fade and water recovery test procedures are computed in a similar manner, yielding the following results:

Fade Tow Forces:

	Kawasaki	Harley-Davidson
(Front only)	131 lb.	191 lb.
(Rear only)	88 lb.	166 lb.

Water Recovery Tow Forces:

	Kawasaki	Harley-Davidson
(Front only)	75 lb.	115 lb.
(Rear only)	69 lb.	121 lb.

Effectiveness Test - Iteration on Tow Heights

In addition to the tow force calculations defined above, there is the need to calculate the tow height required for the effectiveness tests. As has been discussed, selection of tow height for single-wheel traction-limited tests requires an iterative procedure to obtain the correct tow height because, for traction-limited cases, the choice of tow height affects vertical load and, hence, peak traction force. Since the correct tow height is that which provides vertical tire loads corresponding to the free-stopping case, the correct tow height under single-wheel braking must be found by a systematic search process which can be reduced to an efficient exercise in the field through prior generation of a table-lookup suited to each test motorcycle. Using the parametric measurements described earlier, the iteration formulas (see Equations (16) and (17) in Section 3.3) can be solved to provide tables such as appear in Appendix B. These tables serve to guide the selection of the next tow height as a function of the presently (or last) measured tow force. The tow-test iteration tables generated for the Kawasaki and Harley-Davidson (as presented in Appendix B) were obtained for a range of possible values of μ_r and FT_i, using the cited formulas.

Hardware Preparation

For each motorcycle to be tested, three hardware items (tailored to the specific bike) need to be fabricated: (1) an extended front axle shaft, (2) a connecting bracket for the roll stabilizer cross link, and (3) a clevis attachment for connecting the upper tensile link to the motorcycle handlebar.

In addition to these linkages, installation of thermocouples in the front and rear brake linings is required. Strain gauges and/or pressure transducers for measuring front and rear brake actuator forces also need to be installed.

In summary, the test preparations include: (1) parameter measurements, (2) calculation of tow-test conditions based upon the measured parameters, and (3) the installation of tow-connection parts and transducers.

3.5.3 Results of the Demonstration Tests. The test results discussed here derive from the conduct of the test procedure specified in Section 3.3. Two of the motorcycles (Kawasaki and Harley-Davidson) tested in the FMVSS 122 test series served as the test bikes for the demonstration series. These latter tests were conducted on the Dana Corporation's 1 3/4 mile test track oval located near Ottawa Lake, Michigan. The detailed test data obtained for each motorcycle and a discussion of same are presented in Appendix B with the overall findings summarized below.

Effectiveness Tests

Initial questions regarding the ease of application of the tow-test effectiveness procedure were answered by the demonstration tests.

As expected, the Kawasaki test vehicle displayed a torque-limited front braking behavior for both the pre-burnish and post-burnish effectiveness tests. However, the front brake did demonstrate an increase of about 10% in effectiveness as measured by the post-burnish effectiveness test. The traction-limited rear wheel displayed no significant change in tire traction during testing. Hence, the final Kawasaki effectiveness results indicated an approximate gain of 7% in total bike braking performance between pre-burnish and post-burnish tests, apparently as a result of the increase in front brake effectiveness.

The Harley-Davidson was selected as one of the demonstration test bikes by virtue of its ability to accrue the front tire's traction limit thereby permitting a realistic test of the front-wheel iteration scheme specified in the effectiveness test procedure. In general, it was observed that the iteration test sequence proceeded quite smoothly with the tow height convergence being obtained in a manner which very nearly duplicated a computerized prediction of the convergent process. (See Appendix E.) With the Harley-Davidson, no perceptible change in braking performance was noted between pre-burnish and post-burnish effectiveness testing. This result is in keeping with the lemma that the braking performance of a traction-limited motorcycle is strictly defined by the traction limits of the tires themselves. Hence, if the longitudinal traction properties of the tires employed on a traction-limited motorcycle are unchanging, no limit braking performance change should be expected to derive from torque effectiveness alterations—as from a burnish sequence.

Finally, the repeatability of peak tow force test measurements was, in general, quite good, displaying 2% maximum variations from the average for the Harley-Davidson and about twice that for the Kawasaki. The greater maximum variation in the Kawasaki repeats is attributed to the fact that the relatively constant level of random noise in the tow force response constitutes a larger percentage of the overall tow force levels with a lighter machine, such as the Kawasaki F9C.

Burnish Procedure

The burnish procedure was easily conducted on both bikes. Maximum steady-state temperatures of about 200°F and 250°F were achieved on the Kawasaki front and Harley-Davidson rear brakes, respectively, both of which displayed a mild degree of steady drag. No significant trends in brake effectiveness, as reflected by actuator force levels, were noted during either burnish sequence. The burnish spot-check data are shown in Appendix B for both bikes.

Thermal Loading (Fade) Tests

Even though a severe energy rate is prescribed by the thermal loading of the tow-test procedure, with maximum temperatures approaching 300°F and 400°F on two of the test brakes, no significant changes in brake system effectiveness were observed. This result is in general agreement with, but covers a broader energy range than, results obtained during the FMVSS 122 testing. Tow and actuator forces as well as the calculated values of faded system gain are tabulated in Appendix B for both bikes.

Wetted Brake Tests

The conceptual differences between the wetting condition imposed by the tow test and that imposed by FMVSS 122 are made evident through comparison of the wet-brake results from the demonstration test procedure and those obtained from the FMVSS 122 tests. The tow-type demonstration tests indicated no water sensitivity for the drum brakes tested on the Kawasaki. This finding contrasts with that obtained during the earlier FMVSS 122 tests wherein residual losses in brake effectiveness were noted on the same motorcycle.

The demonstration tests for the Harley-Davidson, equipped with disc brakes front and rear, indicated a measurable water sensitivity only for the front brake. Of course, the realism of the tow-test procedure provides that a considerably larger percentage of the airborne spray will impinge upon the front brake assembly. A conclusive statement on this observed water sensitivity is not in order, however, because of the limited tests performed and because of difficulties associated with precise definition of the water environment which results from the spraying technique. However, it is apparent that the wetting procedure does permit a realistic assessment of potential water sensitivities of the disc brake.

3.5.4 Miscellaneous Observations on the Demonstration Tow-Test Results. During, and subsequent to, the demonstration tow tests, various observations were noted relating to the test procedure and the data measurements. Whereas most of these observations are of secondary importance and some of a detailed nature, they may serve to provide a better total understanding of the test procedure, particularly when coupled with analyses such as appear in Appendix E.

Cycle/Rider Configuration Under Tow

The quality of ride of the mechanical towing system while under tow and the sense of safety/controllability by the rider were matters of concern that were not easily answerable prior to construction and testing of the towing rig. However, it was soon noted during the initial testing that the towing rig combination did provide a stable and comfortable feeling for the test rider. The only significant oscillation was that produced during heavy front wheel braking near the traction peak, involving a small oscillation of the wheel on the tire spring. This problem was virtually eliminated through the incorporation of an automotive-type shock absorber within the tow linkage arrangement.

Test Procedure Efficiency

The time required for completion of each element of the test procedure was found to be less than one hour, with the exception of the burnish procedure which required approximately five hours. Total testing time per bike thus amounted to approximately nine test hours—easily accomplished within two test days, allowing also for set-up of a new test vehicle and for instrument calibration.

Tow Force Signal

The tow force signal as measured by the load cell was filtered lightly by the electronic circuitry before being displayed on the monitoring devices and to the test rider. However, a small amount of noise, primarily due to road surface irregularity, was nevertheless present. If not properly accounted for, this noise component could be a source of bias in certain measurements. For example, if peak-hold electronic circuits are allowed to operate upon the described signal, the peak value obtained will be biased high due to the noise component.

With regard to the meter display, the tow force signal presented to the rider should be responsive but at the same time contain a minimum amount of noise so as to be easily read. Too much filtering in the rider's display can produce a sluggish or oscillatory response in the rider's modulation of braking input force.

Rear Tow Height Considerations

Appendix B addresses the matter of aerodynamic pitching moment, establishing that this moment can have a significant influence on the calculation of rear normalized braking coefficient, μ_r. Hence, during the Kawasaki testing, the original μ_r equation, (No. 15) was modified to include aerodynamic effects.

Another significant observation was that there appears to be little need for precise specification of rear-only tow height. That is not to say that the aerodynamic pitching moment effects can be ignored, but that having accounted for the aerodynamic pitching moment, one rear-only tow height is about as valid as another.

There are two significant reasons for this conclusion. Firstly, available data on the longitudinal traction properties of motorcycle tires [3] indicate rather small sensitivity of normalized peak friction coefficient to vertical load variations for motorcycle tires. The limited testing performed during the course of this project also indicated the same result. If this is the case, then clearly the measurement of μ_r by the rear-only tests can be performed at any height with an incurred error bounded by the small load sensitivity of the tire.

The second reason for de-emphasizing concern over uniqueness of a rear-only tow height is adequately given by the error analysis appearing in Appendix E. The interesting conclusion reached there is that even for moderate μ_r load sensitivities of motorcycle tires and a fixed rear-only tow height of twice the c.g. height, the maximum error incurred in total bike deceleration is less than .003 g's.

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4.0 RECOMMENDATION FOR A NEW FEDERAL BRAKING STANDARD FOR MOTORCYCLES

This section presents a recommendation for application of the methodology developed in this study to a revised motorcycle braking standard. First, the various components of the revised standard are discussed, as they must be formulated to accommodate a tow-test procedure. Then, in the following two sections, peripheral considerations to the revised standard are presented, covering the matter of motorcycle braking in a turn and those concerns related to the future applicability of a new standard to a motorcycle market wherein brake system technology is continually evolving.

4.1 Components of a Recommended Standard

The complete formulation of a federal braking standard typically encompasses a seven-item prescription, covering:

1. Scope
2. Purpose
3. Application
4. Definitions
5. Requirements
6. Test Conditions
7. Test Procedures and Sequence

Among these, the scope, purpose, and application of a motorcycle brake system standard have already been established. Given that these three aspects of a motorcycle braking rule remain as NHTSA policy (presumably reflecting a traffic safety need), the developments occurring in this project are seen as impacting only upon the latter four items in the envisioned refined standard.

4.1.1 Definitions. The employment of a tow-test methodology requires that certain terms be defined which may not be of universal meaning as they are applied in the developed test procedure. Accordingly, we define the following terms in the context of a motorcycle tow-test braking procedure:

"Tow height"—the vertical distance between the ground plane and the centerline at which the tow force acts.

"Tow force"—the longitudinal force, acting in a horizontal plane, which reacts the summation of braking and drag forces exerted by a motorcycle during test.

"Front-only" tests—those brake actuation procedures in which the front brake is applied alone with the tow height set to a specified front-only value.

"Rear-only" tests—those brake actuation procedures in which the rear brake is applied alone with the tow height set to a specified rear-only value.

4.1.2 Requirements. Clearly, the specification of performance requirements need to be made in a manner that is suited to the tow-test procedure. Such performance specifications will differ from those currently required under FMVSS 122, principally in terms of performance levels rather than in terms of format. Requirements for effectiveness performance will be specified in terms of stopping distance, as has been discussed, but the compliance levels appropriate for stopping distances measured by the tow method would be presumably shorter than were specified in FMVSS 122 if the same overall braking capability level were to be desired. This general contrast in level requirements derives from the ideal character of tire traction utilization which is embodied within the tow-test-determined stopping distances. For example, in our (a) rider-controlled and (b) towed tests of the Kawasaki F9C, the corresponding stopping distances from 60 mph were 160 feet versus 154 feet, respectively. Accordingly, if the compliance levels in a tow-test braking standard were specified to reflect the characteristically shorter distances such as found in this example, the resulting requirements would appear nominally more demanding while actually reflecting only a new scale of measurement.

Going beyond that generalization, specific requirement levels are not suggested here since no adequate basis seems to exist for their specification. Further, it is our conviction that more and new information needs to be obtained on the broad definition of safety quality as derives from braking performance. Such a definition must account for the extent to which stopping distance capability may, beyond a certain performance level, become a characteristic which directly conflicts with rider ability to modulate the brake. This concern is particularly pertinent to the case of motorcycle braking systems since (a) front-wheel lockup virtually assures loss of control, but (b) the front brake must possess a high level of torque effectiveness if "minimal" stopping distances are to be achieved. Thus, insofar as no data base exists indicating the factors influencing the braking modulability of motorcycles, it is not possible for us to appreciate the tradeoffs in motorcycle safety implied by stopping distance requirements, taken alone.

More importantly, perhaps, a comprehensive revision of the motorcycle braking standard would seem to require the incorporation of certain specifications relating directly to the rider's ability to modulate braking. When the basis for such a specification has been established, requirement levels for the control input properties of the brake system, as well as stopping capability, can be made as complementing features.

Additionally, the specification of the stopping capability to be achieved by a partially-braked cycle can be directly accommodated by a tow-test rule as soon as the basis for specific requirements is established. Indeed, the nature of the tow-test approach with its single-wheel-braking procedures affords partial system measures as an immediate product.

With regard to the specification of requirement levels for resistance to thermal loading and water exposure, a different view of the same concerns expressed above seems to emerge. If the quality of a braking system is subsumed within its ability to provide a stopping capability and to provide it controllably, then the sensitivity of the brake system to extraneous conditions is relevant in terms of these features, as well. Thus, we would hypothesize that "fade" and "water" sensitivities are safety relevant to the extent that stopping capability and/or modulability is compromised.

Limit stopping capability will be compromised as a result of fading when the reduction in brake torque effectiveness at either wheel reaches a level at which:

1) a torque-limited brake (given the vehicle load and the tire-pavement friction level) suffers a reduction in its torque limit which compromises the stopping distance, or

2) an otherwise traction-limited tire/wheel/brake assembly suffers a reduction in the torque effectiveness of the brake such that accrual of the tire's traction peak is no longer possible and the new resulting torque-limited output "significantly" extends the minimum stopping distance.

The third possibility, of course (for which stopping capability is not compromised), involves that traction-limited brake system whose sensitivity to thermal or water exposure does not render it incapable of still accruing the tire's traction limit. By way of clarification, Figure 17 illustrates the three possibilities mentioned. The brake system at the left is basically incapable of achieving wheel lock at the reference load and pavement condition and thus becomes most influenced by the fade response of rubbing elements because of the large fractional loss in stopping capability per unit of reduction in the brake torque limit. The system represented in the middle becomes brake-torque limited to a degree determined by the dimensions of the "margin" afforded by the baseline output and by the net torque decrement accompanying fade. At the right, the system which is traction-limited in its baseline condition remains traction-limited when

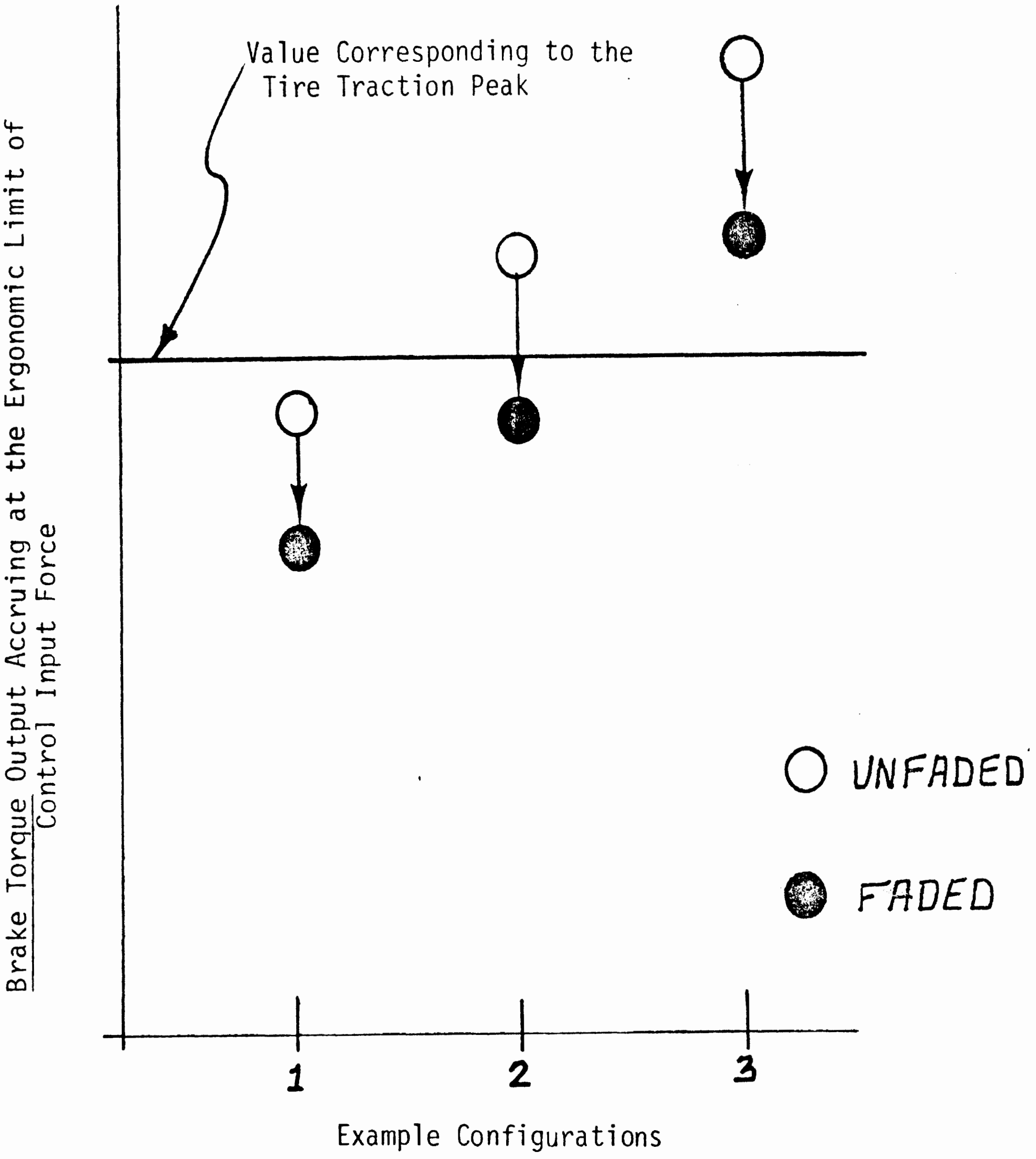

Figure 17. Example fade-induced changes in the brake torque limit with respect to the torque level needed to reach the tire traction peak.

"faded" if its original margin is sufficiently great and/or if its fade decrement is sufficiently small.

Accordingly, there is no generally applicable relationship between brake torque effectiveness and vehicle stopping capability. A regulation serving to minimize the fade decrement, however, will obviously act to preserve baseline stopping capability, regardless of the specific situation which applies.

Further, the minimization of thermal and water sensitivities will serve to fix brake gain characteristics such that the baseline modulability of the system is retained. Since both stopping capability and brake system modulability would appear to be assured through maintenance of the actuator limit force/brake torque relationship, the specification of a tow-test actuator-force gain seems a reasonable format for fade requirements.

The dimensions of the allowable decrement in this gain measure should, most desirably, be based upon findings to be obtained in further research. It would be rather straightforward to establish, on the basis of stopping capability, a reasonable maximum allowable decrement in brake system gain. Stopping-distance increases implied by the torque-gain decreases in torque-limited brake system can be practicably assessed through a survey project using the tow-test methodology. Requirements intended to constrain the brake-gain decrement so as to assure the retention of modulability, however, should be derived from a human-factors oriented research program as has been cited earlier to gain an understanding of the principles of rider-cycle interaction during braking.

Irrespective of the particular findings which may derive from such research, it is believed that the basic concept of tow testing is sufficiently adaptable that a variety of response characterization formats could be accomplished.

4.1.3 Test Conditions. Relative to the specification of test conditions, it appears that certain features of FMVSS 122 should remain unchanged. Specifically, we see that 122 test condition specifications still apply concerning:

Tire inflation pressure	(item S6.2)
Ambient temperature	(item S6.5)
Wind velocity	(item S6.6)
Thermocouples	(item S6.9)
and Brake actuation forces	(item S6.10)

The remaining test condition specifications are not recommended for adoption in a revised standard based on a tow-test methodology. Specifically, we recommend supplemental specifications as follows:

Tire Loads - Vertical load on each motorcycle tire, at rest, shall be within that range of values which derives from the as-designed distribution of unloaded vehicle weight plus a 150- to 200-lb rider seated in a natural riding position.

> (Rationale: This definition allows for (1) a range of rider weights, (2) a margin of adjustment in acceptable tire loading as may be required to accommodate small variations in the mass distribution of tow linkages and actuator force transducers, (3) minimal impact upon tow-test results since tire loads become normalized in the effectiveness measures.)

Transmission - All towing tests shall be conducted with the transmission disengaged from the drive wheel(s).

> (Rationale: This definition differs from FMVSS 122 insofar as it generalizes the transmission's state of uncoupling.)

Engine - (there is no specified engine condition)

Road Surface - (There should, indeed, be a road surface constraint, although our recommendation is that the pavement friction level be normalized according to a braking efficiency method such as has already been developed under NHTSA auspices [4]. With such an approach, virtually any non-deformable surface is acceptable for test. Further, the traction limits of motorcycle tires can be comprehensively evaluated if they constitute a constraint on vehicle braking capability.)

Vehicle Position - (No specification of vehicle position is needed, as has been the case in the free-stopping procedure of FMVSS 122.)

Test Speed - During brake application the velocity of the motorcycle should be retained within 1 mph of the value specified in each procedure.

Towing Connection - The tow force is applied to the motorcycle so that, during brake application, complete freedom of suspension travel is permitted while the effective height of tow force application is retained to within one inch of the value measured with the motorcycle at rest.

> (Rationale: The specification of a 1-inch tolerance in tow height accounts for the influence of tire deflection under load and also permits a limited vertical displacement of towing linkage elements. This tolerance permits a variation in the pitch reaction moment on the order of 1 to 3%.)

Other Motion Constraints - The motorcycle may be restrained in its roll degree of freedom (that is, rotation about a longitudinal axis). The motorcycle may also be restrained in either its steer or yaw degrees of freedom (that is, rotation about axes that are essentially vertical). Roll, yaw, or steer constraints must not, however, impose a pitching moment reaction on the motorcycle nor longitudinal or vertical force reactions.

4.1.4 Test Procedures. It is recommended that the procedural sequence of a revised motorcycle braking standard incorporate the tow-test procedures specified in Section 3.3. With respect to the procedural steps not covered in Section 3.3 but which are included in FMVSS 122, no specific comments can be supported by the investigation being reported here. The two FMVSS 122 test procedures of note that remain, i.e., "Parking Brake Test" and "Final Inspection," presumably are of accepted value as brake system performance checks, and thus are not challenged here.

4.2 Considerations of Motorcycle Braking in a Turn

Considerations were given to the mechanics of motorcycle response to braking in a turn as a subtopic in this study. This topic was seen as pertinent to the overall investigation insofar as there may be a need for a braking-in-a-turn performance measure within a future motorcycle braking standard. While data and calculations presented in this section cannot establish such a need, per se, certain safety-related aspects of motorcycle behavior during curved-path braking can be shown.

The nature of the maneuvering condition in question can be described as the application of braking while the motorcycle is tracking a steady curve at a somewhat elevated level of lateral acceleration. To sustain the initial steady turn the motorcycle must be inclined to provide a roll moment balance and must also be steered to achieve a balance of side forces as well as yaw moments. From that rather delicately-tuned condition, the application of braking effort holds a prospect for disturbing the turn since:

1) the tires must now generate longitudinal, or braking, shear forces in addition to lateral or cornering forces

2) the longitudinal transfer of vertical load resulting from deceleration imposes a basic change in each tire's operating condition

3) the changes in camber thrust output of each tire caused by changes in vertical load and the imposition of braking slip require that the slip angles of each tire (usually very small during non-braking maneuvers) adjust to "take up the slack" and reestablish side force and yaw moment equilibrium.

Beyond the question of disturbing the turn, there is also interest in the degree to which the curved-path condition tends to reduce the maximum stopping capability of the motorcycle. The potential for degradation in stopping performance derives from a conflict in tire shear force generation under conditions combining inclination angle and longitudinal and lateral slip.

Since the properties of motorcycle tires clearly play a major role in determining the response of the cycle under the curved-path braking condition, tests were performed to provide a data base of the combined slip behavior of motorcycle tires. Four tires were selected and tested on the HSRI flat-bed tire test machine—a slow-speed laboratory device, quite suited to making traction measurements within the non-friction-limited regime. Although the full set of those data are presented in Appendix F, results will be summarized here and interpreted in the context of total vehicle behavior.

Tests were conducted under conditions of constant slip angle (α), inclination angle (γ), vertical load, (F_z), and longitudinal slip (s). As a means of limiting the scope of the combined slip matrix, measurements were made over various slip-angle conditions, with zero inclination, and over various values of inclination angle, with zero lateral slip. At each condition of wheel plane orientation, a set of longitudinal slip conditions were examined covering the range from 0 to 20% slip. Some example results are shown in Figure 18, which illustrates the changes in the slip-angle and camber-angle carpet plots which derive from the 20% longitudinal slip condition. As shown, both of the major mechanisms of side force generation are significantly influenced by longitudinal slip.

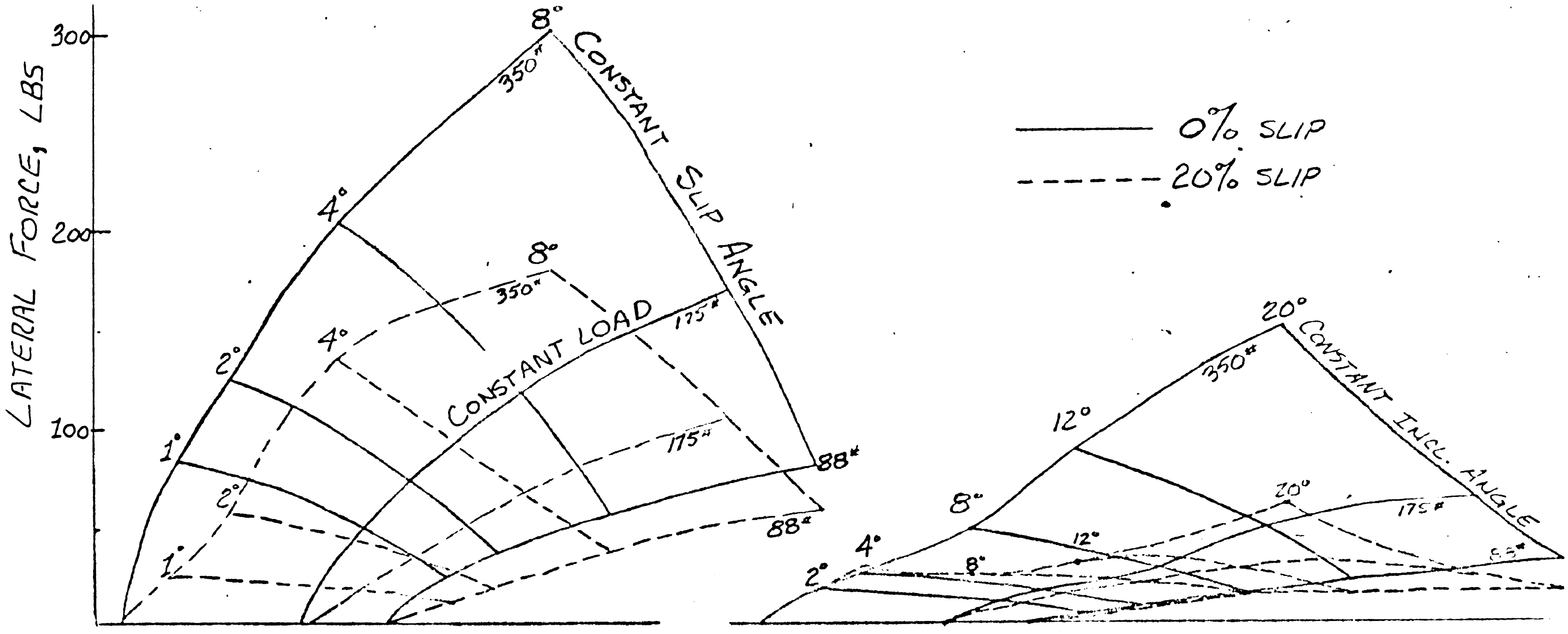

Figure 18. Lateral force carpet plots at varying slip angle and inclination angle for a 4.00 x 18 motorcycle tire.

An important feature of these data, however, is the extent to which they illustrate the previously unexplored sensitivity of camber thrust to longitudinal slip, given that the cornering motorcycle generates virtually all of its needed side forces through the camber thrust mechanism. Thus it is significant that no exaggerated sensitivity of camber thrust to longitudinal slip has been observed. This judgment is based upon comparisons between the "fall-off" in α- and γ-induced side forces with increasing slip over the range of side force which is reasonably available through the camber thrust mechanism. For example, in the data of Figure 18, we see that the side force exhibited by the freely-rolling tire at a 2° slip angle is comparable to that developed at about 16° camber angle for the 350-lb load condition. Imposing the 20% slip condition, side force due to slip angle falls to 45% of its zero-slip value while camber thrust falls to about 35% of its zero-slip value. At the lower loads, this contrast tends to reverse, with side force due to camber thrust falling off less than side force due to slip angle.

Figures 19 and 20 serve to summarize these sensitivities for one tire over a range of loads by illustrating the ratio of side force during braking (F_y) to free-rolling side force (F_{y_o}) at a steady slip angle of $\alpha = 2°$ (in Figure 19) and at a steady inclination angle of $\gamma = 20°$ (in Figure 20). The reduction in side force with increasing longitudinal slip is compared on each plot with an overlay of the corresponding behavior which has been measured on a sample of passenger car tires at a 4° slip angle [5]. The overlay illustrates that on the basis of tire properties alone, one would not expect the motorcycle's reliance on camber thrust to render braking-in-a-turn performance which differs, in any gross way, from the equivalent performance exhibited by passenger cars.

On plotting results for all four tires at a single value of vertical load, Figures 21 and 22 are obtained. We see that the overlay of passenger car tire data constitutes a not unreasonable envelope of the motorcycle tire data either for the case in which side force is produced by lateral slip or inclination. For a broader evaluation of the various slip conditions not represented here, the reader is referred to Appendix F.

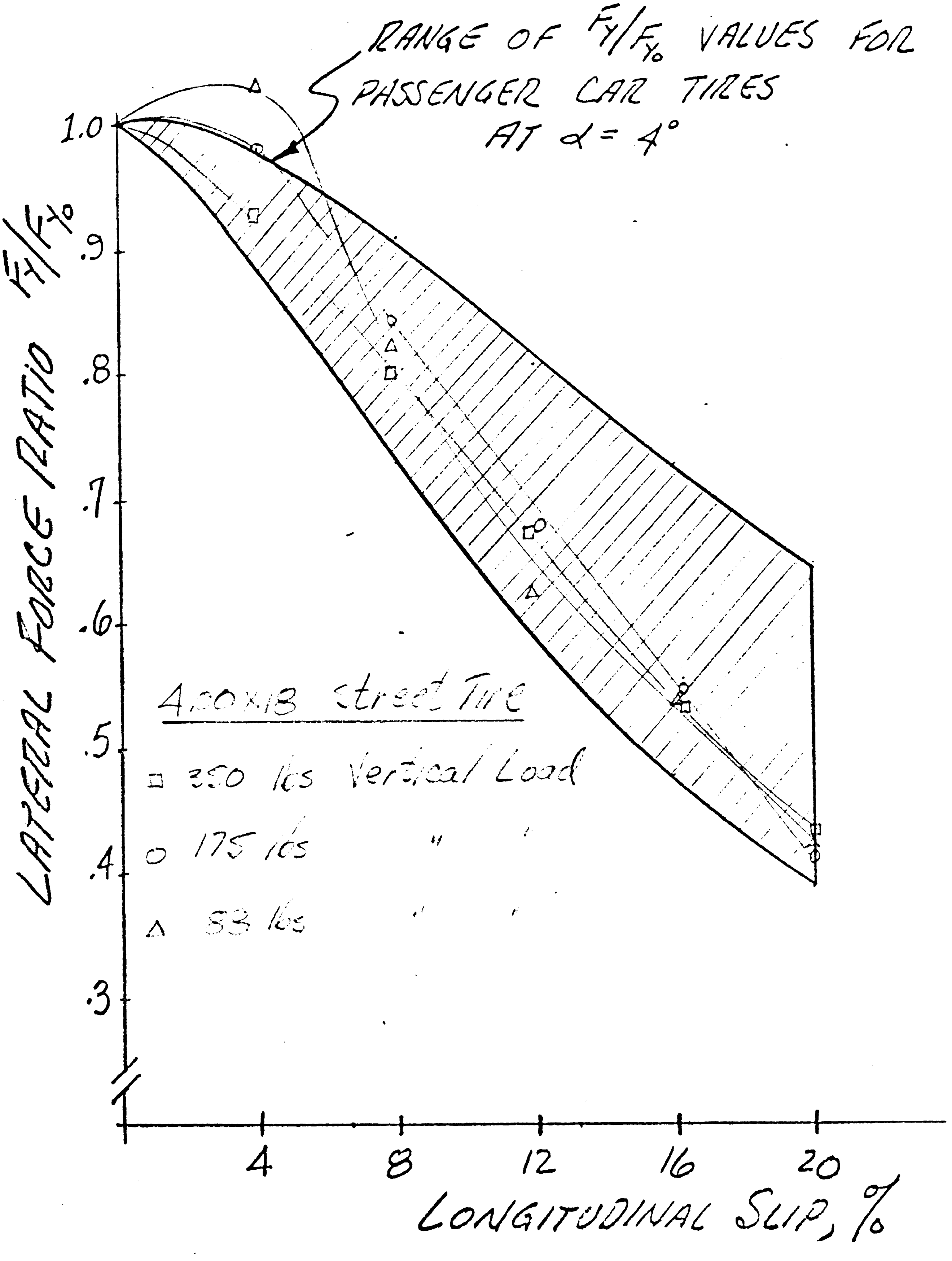

Figure 19. Fall-off in F_y/F_{y_0} with increasing s for a motorcycle tire at $\alpha = 2°$ compared to an envelope of passenger car tire responses measured at $\alpha = 4°$

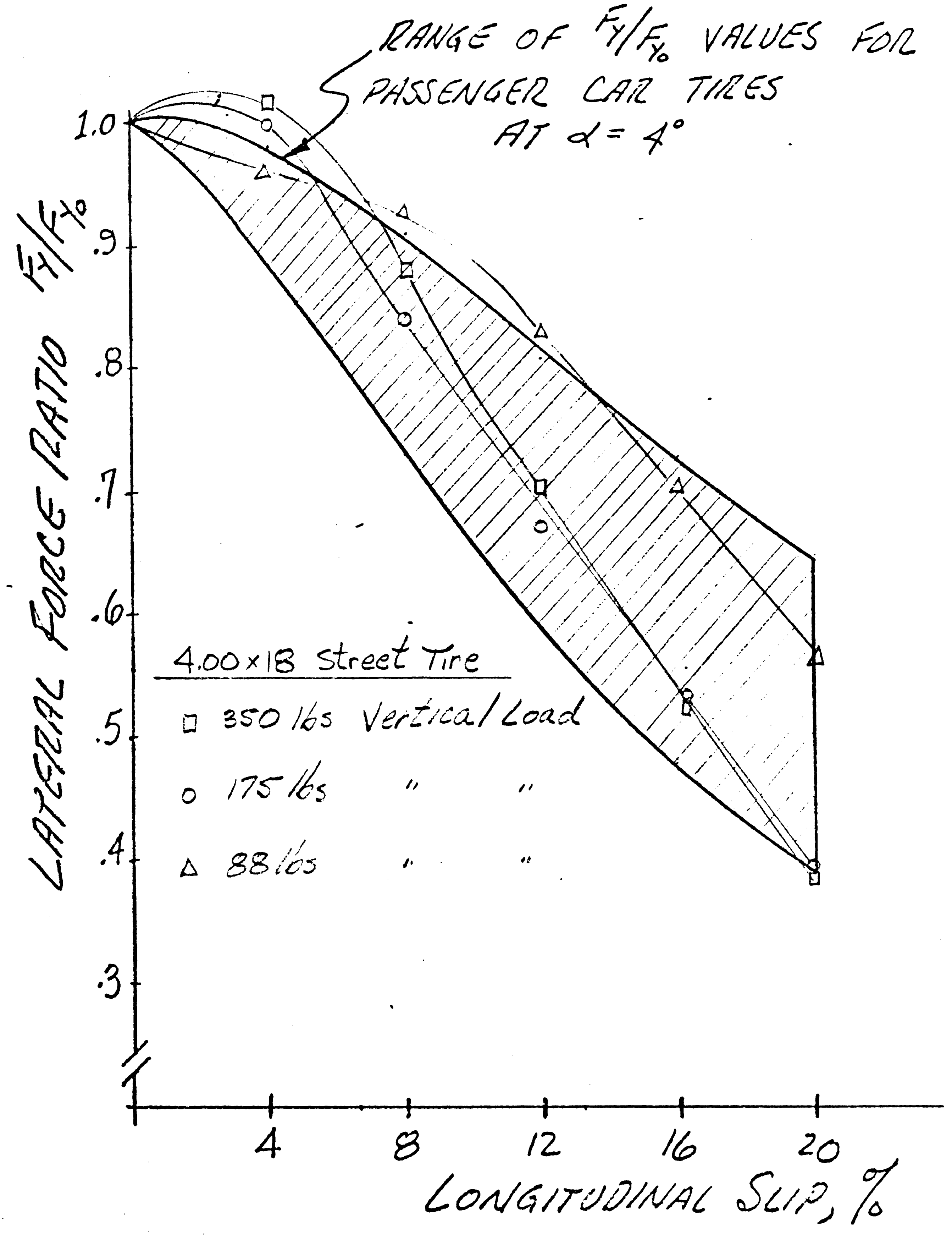

Figure 20. Fall-off in F_y/F_{y_0} with increasing s for a motorcycle tire at γ = 20° compared to an envelope of car tire responses measured at α = 4°.

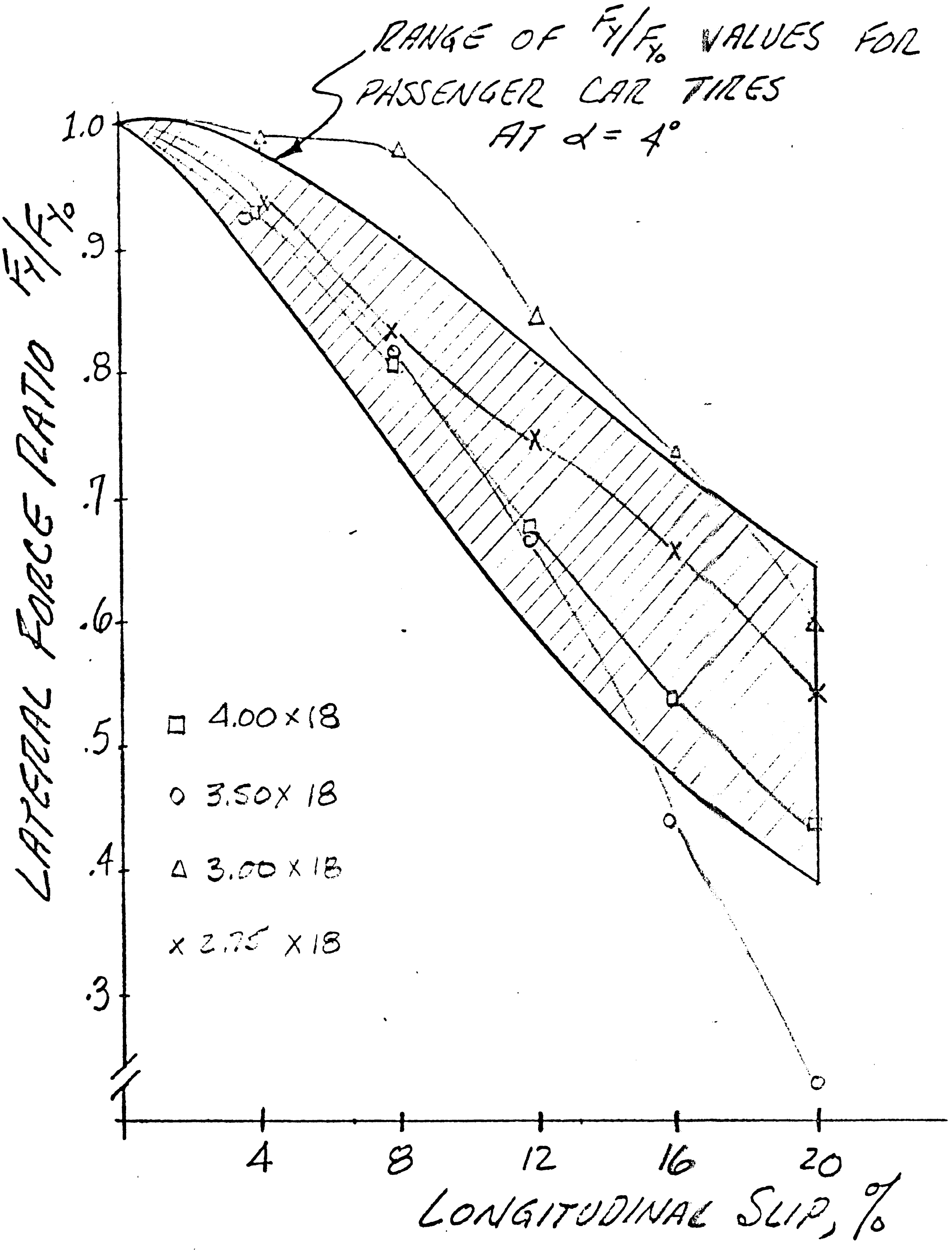

Figure 21. Fall-off in F_y/F_{y_0} with slip for four different motorcycle tires at α = 2° compared to envelope of car tire responses measured at α = 4°. Motorcycle tires all operated at a nominal static (motorcycle plus rider) load.

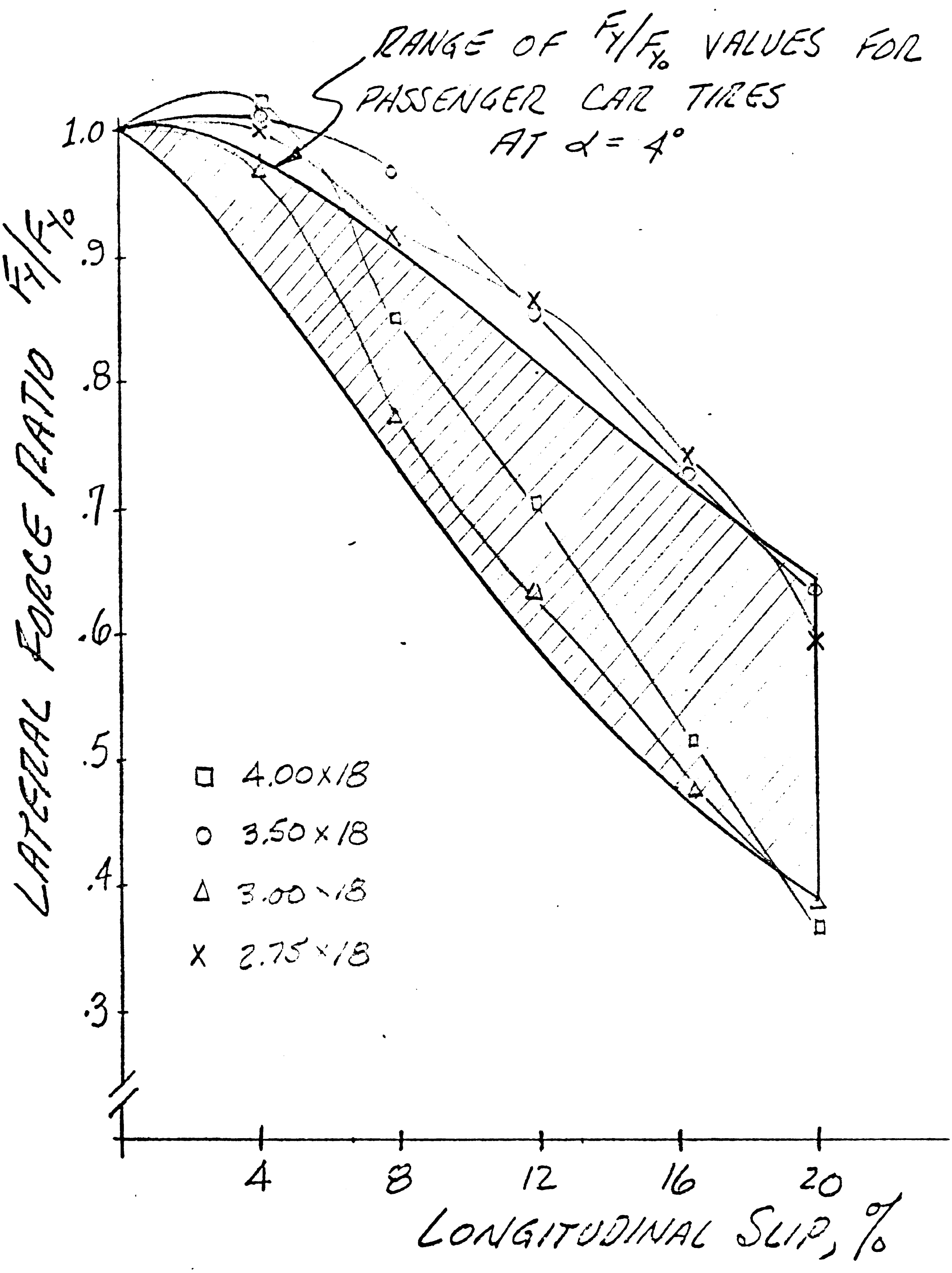

Figure 22. Fall-off in F_y/F_{y_0} with slip for four different motorcycle tires at γ = 20° compared to envelope of car tire responses measured at α = 4°. Motorcycle tires all operated at a nominal static (motorcycle plus rider) load.

A comprehensive study of the mechanics of the braking-in-a turn response of motorcycles was beyond the scope of this study. A useful, simplified view can be obtained, however, from a static analysis around a given operating point. To develop this analysis, consider firstly that, in a steady turn, the motorcycle will (to a good approximation) sustain roll equilibrium by inclining to an angle, ϕ, as defined below:

$$\phi = \tan^{-1} \frac{A_y}{g} \tag{20}$$

where A_y is lateral acceleration (ft/sec^2)

Further, to sustain yaw equilibrium, lateral tire forces must be generated at the front and rear tires according to Equations (21) and (22)

$$aF_{y_f} - bF_{y_r} = 0 \tag{21}$$

$$F_{y_f} + F_{y_r} = A_y \frac{W}{g} \tag{22}$$

Since the lateral forces will be determined by the vertical loads, F_{z_f} and F_{z_r}, on the front and rear tires, it is necessary to account for load transfer during braking if we are to examine braking-in-a-turn behavior. Accordingly, we write the familiar expressions for load transfer, viz.,

$$F_{z_f} = \frac{b}{a+b} W + \frac{h}{a+b} \frac{A_x}{g} W \tag{23}$$

$$F_{z_r} = \frac{a}{a+b} W - \frac{h}{a+b} \frac{A_x}{g} W \tag{24}$$

In order to employ measured tire data with a minimum of interpolation for a specific example, let us consider the 20° inclination angle condition for which a lateral acceleration of

0.36 g obtains. At this lateral acceleration level and for values of a, b, and W as measured during this study on the Kawasaki F9C motorcycle we find from Equations (21) and (22) that the following side forces must be produced by the front and rear tires:

$$F_{y_f} = 61.8 \text{ lbs}$$

and

$$F_{y_r} = 105.6 \text{ lbs}$$

Thus for the subject motorcycle to maintain a steady turn which is characterized, at a given point in time, by a 0.36 g lateral acceleration, it must maintain a 20° inclination or roll attitude and it must generate the lateral forces shown. It can be quickly appreciated that the critical influence on the vehicle's ability to maintain the described turn under increasing levels of braking is the loss in rear tire load due to load transfer.

As shown in Figure 23, the vertical load on the rear tire drops off so quickly with increasing A_x that F_{z_r} actually equals F_{y_r} at an A_x value of .83 g's. This implies that even in the absence of any brake torque applied to the rear wheel, a lateral traction coefficient of $\mu_y = 1.0$ would be required to permit a deceleration of .83 g to be achieved. Clearly, the realistic maximum value of A_x must be somewhat less than .83 (given a $\mu_y = 1.0$ constraint) since a certain participation of the rear brake is, in fact, required.

To evaluate the lateral force produced at the rear tire under conditions of increased braking, the data gathered on a Continental 4.00 x 18 street tire has been employed to generate the F_{y_r} curve shown on Figure 23. As shown, an increasing A_x results in a declining lateral force, as generated by a 20° inclination angle. This reduction derives from the increasing longitudinal slip, since this calculation of F_{y_r} has presumed a braking input of

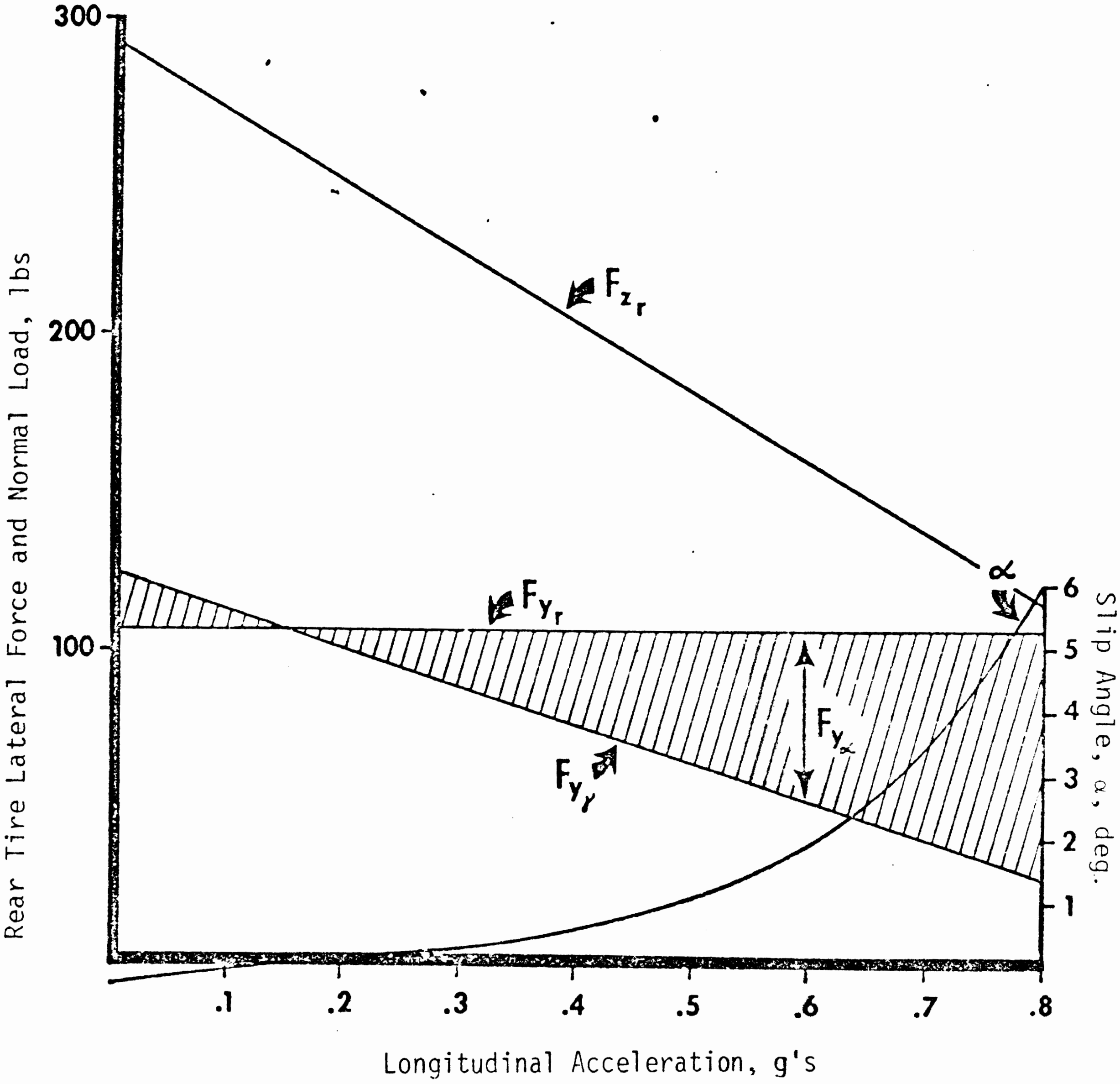

Figure 23. The changing role of camber (γ) and slip angle (α) mechanisms of side force generation of the rear tire of a Kawasaki F9C-type motorcycle while braking in a turn of 0.36 g A_y.

$F_{x_r} = A_x/g \, F_{z_r}$ (that is, the rear tire contributes a braking force that is "ideally" proportioned to its vertical load). Since the requirement for a rear tire side force remains fixed, however, the decreasing value of side force due to inclination angle must be augmented by a newly-developed side force due to slip angle. Accordingly, an increasing value of F_{y_α} must be generated, as shown in Figure 23, by means of a reorientation of the motorcycle's rear frame to produce the slip angles plotted for the rear tire. To be rigorous, we now have the full complement of combined, and interactive, traction conditions, namely, longitudinal slip, camber angle, and slip angle. Thus the plotted slip angle curve shows values which are somewhat less than that required for sustaining yaw equilibrium during braking—since the tire measurements made in this study were obtained under conditions of varied α, s, and F_z (with $\gamma = 0$) and also, γ, s, and F_z (with $\alpha = 0$) rather than under the full, and rather awesome, matrix of α, γ, s, and F_z conditions. A spot check of the side force produced under a full set of combined slip conditions has indicated that yaw equilibrium might actually require slip angles of approximately twice the values plotted in Figure 23.

The crude analysis generating Figure 23 serves to quantify the directional or yaw features of the motorcycle's response to braking in a turn. Thus, we might hypothesize that the α history in Figure 23 is related to the magnitude of the yaw perturbation which will accrue, since the rear frame must slew to a sideslip virtually equal to the values of α indicated in the figure as a consequence of the brake input.

A direct means of evaluating the vehicle's deceleration is to employ a simple "friction circle" model of the tire rather than by using direct measurements of the interactive traction forces. By such an approach, the shear force and vertical load plots for the rear tire (only) can be obtained as shown in Figure 24. In this presentation, the rear tire's generation of an "ideally" proportioned longitudinal force, F_{x_r}, together with the constant

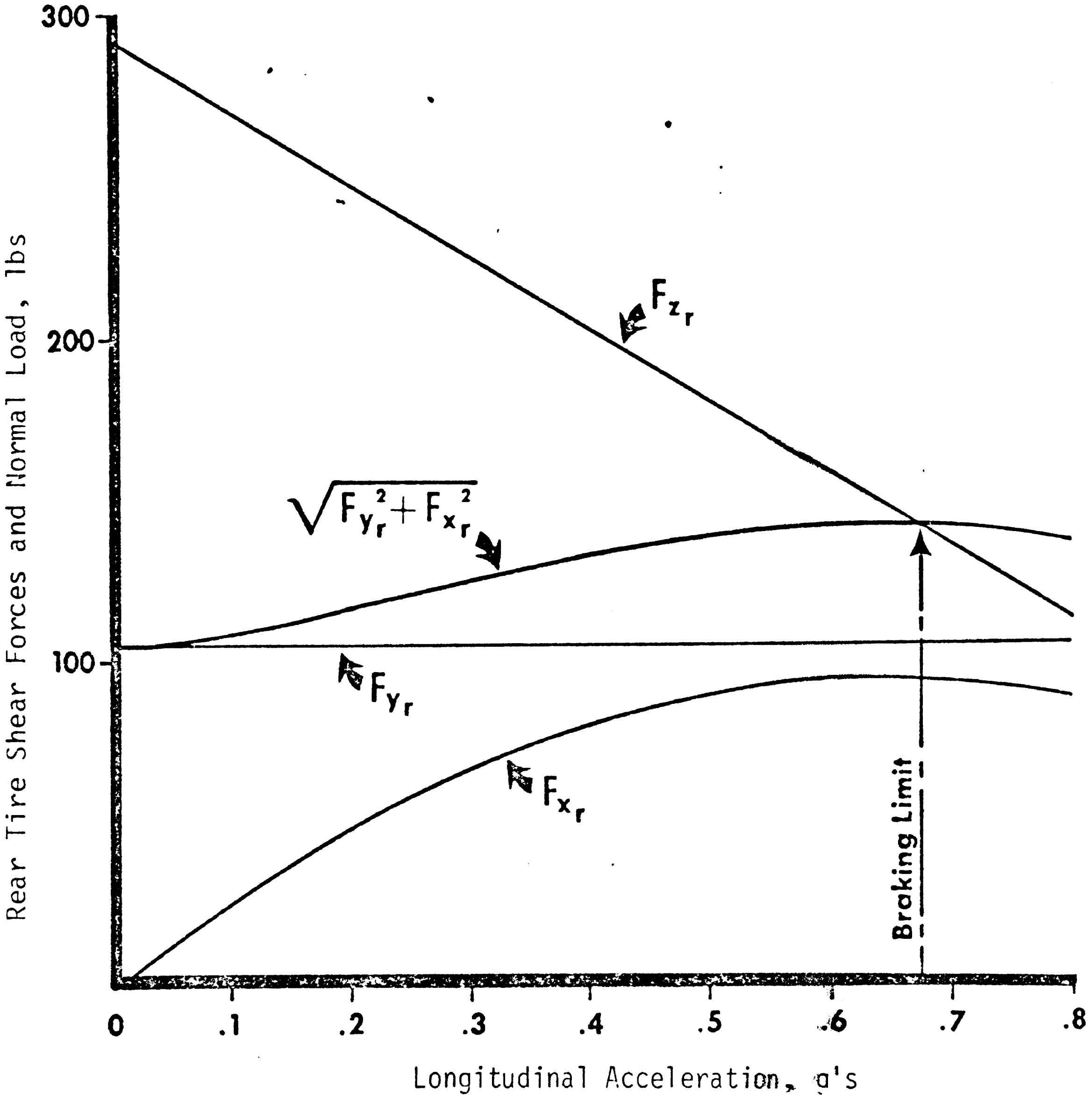

Figure 24. Lateral, longitudinal, and resultant shear forces and normal load prevailing at rear tire during braking in a 0.36 g A_y turn. Proportioning is such that $F_{x_r} = A_x/g(F_{z_r})$.

lateral force, F_{y_r}, required by the curved path, are consolidated into a resultant traction force. The point at which this resultant crosses over the vertical load curve establishes the limit level of longitudinal acceleration, A_x, which can be attained while braking in the specified turn on a surface yielding a peak tire-traction coefficient of 1.0. From Figure 24, which assumes an "ideal" proportioning of braking forces, we find that the limit value of A_x is 0.67 g's.

Clearly, the precise value of a theoretical limit in A_x capability is dependent upon the proportion of braking force which is generated by the rear tire. An interesting illustration of this dependency can be obtained by considering the braking limit in a 0.36 g turn which accrues for a vehicle with the same baseline parameters, but which employs a single-control brake system of the type designed by the Moto Guzzi Company (as detailed in Appendix D). As shown in Figure 25, this constant proportioning function yields the rear tire longitudinal force relationship:

$$F_{x_r} = .432 \frac{A_x W}{g}$$

The resultant shear force (with constant lateral force) inscribes a function which now intersects the F_z curve at 0.59 g's, A_x, indicating that a motorcycle configured like the Kawasaki F9C, but outfitted with a single-control brake system (proportioning brake torque to achieve simultaneous front and rear lockup on a surface of $\mu = 0.4$) cannot exceed a deceleration of 0.59 g when braking in a turn consisting of a lateral acceleration equal to .36 g on a tire/surface condition characterized by $\mu_{peak} = 1.0$. At the deceleration level of .59 g, the motorcycle will become directionally unstable because of a saturation in the lateral force capability of the rear tire. It is quite likely, furthermore, that a rigorous treatment of tire shear force functions would indicate a yaw instability in the non-saturated regime of shear forces thereby reducing the usable braking limit from 0.59 g to an even lower value.

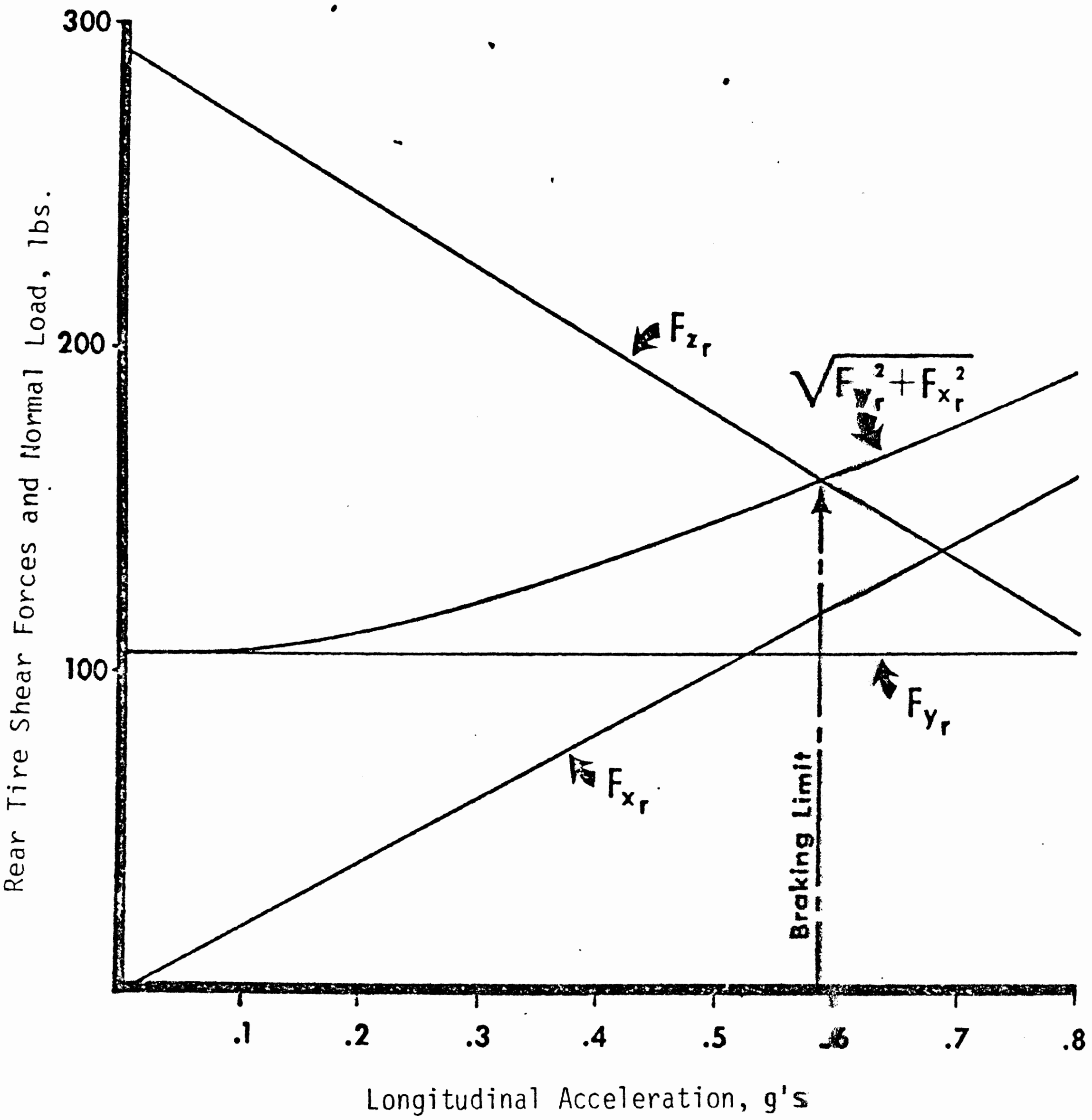

Figure 25. Lateral, longitudinal, and resultant shear forces and normal load prevailing at rear tire during braking in a 0.36 g A_y turn. Proportioning is such that $F_{x_r} = .432 A_x/g(W)$.

These analyses have served to illustrate the mechanisms by which a yaw perturbation is generated and to estimate the constraint on deceleration capability which might be expected in an example case of braking in a turn. Taking a broader perspective of the safety implications of the motorcycle braking-in-a-turn maneuver, it would appear that the rider's ability to modulate his braking actuator inputs to avoid wheel lockup is, perhaps, the key issue. Since the turn condition implies that a bias value of roll moment is being sustained by tire side forces, the lockup of either tire leads very quickly to a total capsize response. The rollover mode is "preloaded," so to speak, by the initial turn such that the resulting roll divergency rates following lockup will be correspondingly great. While rear lockup in a turn does not absolutely commit the motorcycle to a capsize (a very skilled rider can "de-steer" from the initial curvilinear path onto a tangent path), the normal expectation would be that riders of average skill level could not avoid capsize. Front-wheel lockup in a turn, however, would result in a capsize in virtually every case for which a significant degree of turn severity had prevailed.

The foregoing discussion has tried to shed light on the general nature of motorcycle braking-in-a-turn behavior. Based upon these considerations, one might conclude that this maneuvering condition involves an exceedingly complex problem in vehicle mechanics, not to mention the complexities of the vehicle control task. It would appear that the primary vehicle design parameters influencing response are simply the vertical and longitudinal locations of the mass center—except for the unusual case of the brake system with fixed proportioning.

It is pertinent to note, also, that certain properties of motorcycle response to braking in a turn are at odds with what appear to be typical rider control strategies. Since front-wheel lockup while negotiating a curve is catastrophic, the typical rider will heavily favor rear braking while in a turn. With the mass center located rather aft, however, the rear tire must generate the larger side force to establish a yaw moment balance. Subsequently, as a result of the powerful load transfer mechanism at work (because of the motorcycle's high value of h/ℓ), we find that the rider is demanding the higher braking force output from that tire which is increasingly least capable of supplying it. The front tire, on the other hand, has a lesser side force requirement for retention of the turn and also accrues a larger load during braking. Accordingly, a strategy of emphasizing rear braking while in a turn, although possibly rationalized as assuring a lesser of evils, constitutes a markedly inefficient means of stopping. While the same general conflict exists in the case of straight-line braking, the braking-in-a-turn maneuver does render rear-brake-favoritism an even less efficient control strategy.

Overall, no significant enlightenment of the safety implications of motorcycle braking in a turn appears likely until the difficult matter of closed-loop behavior is effectively explored. Accordingly, abstract measures of vehicle performance properties, taken alone, will remain generally uninterpretable in a safety context until their significance to the rider's ability to extract a maximum braking efficiency from the cycle can be ascertained.

4.3 Considerations Deriving from the Evolution of Motorcycle Brake System Technology

The principal considerations related to the significance of an evolving brake system technology concern the extent to which:

a) a revised vehicle performance standard might become an impediment to improvements in vehicle design,

b) the standard's procedural methods may not be applicable to certain advanced brake system configurations, and

c) the measures of performance contained in the standard might be unsuited to the assurance of safe braking properties for certain advanced brake systems.

In an effort to examine the likely advances in motorcycle braking technology which might warrant special consideration in the revision of FMVSS 122, views were solicited from the motorcycle industry. The solicitation involved a questionnaire which is presented below as it was posed to manufacturers:

1) Please cite design concepts, not currently in common use, but which are likely to be marketed in the next 10 years, which will influence:

    a) The manner in which brake control input elements are applied (e.g., force or stroke specification changes, other (or fewer) control elements).

    b) The manner by which control input efforts become delivered to and distributed among the friction brake elements (e.g., fixed proportioning single element control, partially proportioned systems, power-assisted brake actuators).

    c) The torque production properties of friction brakes (e.g., major changes in brake actuating mechanisms, lining friction gain or thermal/water sensitivity).

    d) The control of brake torque so as to avoid wheel locking (e.g., antilock systems).

    e) The traction limits of installed tires (e.g., tire design for optimizing shear force production, vehicle mass center location as it determines dynamic tire loading).

2) With each item (a-e), please cite the time period within which you would (a) <u>first</u> expect to see the cited advancements marketed and (b) expect to see the advancement in common usage.

3) With each item (a-e), please cite the ball park cost which you would expect to accompany the retail sales price of each cited advancement.

Responses to the above inquiry were received from four manufacturers. A summary of each response is presented below, while the full submissions from each party are presented in Appendix IV.

Kawasaki Heavy Industries, Ltd.

1) Cited an expectation of minor advancement in the matching of brake systems to vehicle type.

2) Also cited minor advancements in water fade sensitivity of disc brakes.

3) Generally discounted the likelihood of any significant usage of (a) power-assisted motorcycle brakes, (b) proportioned systems in which front and rear wheels become actuated from a single element, or (c) wheel-lock control systems.

Suzuki Motor Corporation

1) Regarding proportional systems, cites possibility of future marketability but notes a low limit for the front brake contribution and the need for a supplemental front-only actuator.

2) Predicts that a motorcycle antilock system will appear on the market by 1981, and that such a system may be in common usage by 1983. (A market price of about $170 is expected.)

3) Expects a significant improvement in the traction capability of motorcycle tires on wet surfaces.

Honda Motor Company

1) Expressed an overview position concerning the need for studying the "software" aspects of motorcycle braking, that is (apparently), the control aspects of rider/vehicle interaction.

2) Cited the fundamental requirement of a hand lever-actuated brake because of the need to hold the vehicle at rest while both feet are down for supporting the machine—at a stop light, for example.

3) Sees proportioned brake systems as an unlikely development except as possibly coupled with an antilock system.

4) Does not expect power-assisted brake actuation since it is seen as conflicting with the driver's need for tactile feedback; alternatively, anticipates an improvement in brake effectiveness through refinement of friction materials, improvement of delivery efficiency, and development of self-actuating mechanisms.

5) Does not expect to market a motorcycle antilock system within the next ten years; further, cites the need for examining the merits and demerits of antilock systems usage in the real world riding situation.

6) Expects to see an improvement in the wet traction performance of motorcycle tires.

Moto Guzzi

Moto Guzzi's contribution concerned its "integral braking" system which proportions front and rear brake actuation through the foot pedal.

The submission contains a lengthy engineering analysis upon which the distribution of braking torques is determined. The analysis attempts to proportion front and rear braking so that simultaneous lockup of front and rear wheels occurs at a given friction level. The Moto Guzzi analysis contains errors, however, which tend to confuse the picture, although the final distribution designed into the integral braking system, while more front-biased than might have been expected, is not grossly unreasonable. The errors occur in an expression of the load which is transferred during braking, viz. (using Moto Guzzi's notation)

$$W = \frac{P_p \times f \times h}{L}$$

where

W = weight which shifts from the rear spindle to the front spindle

P_p = total weight supported by the <u>rear spindle</u> in static condition

f = friction coefficient, tire-road

h = height of center of gravity

L = wheelbase

The error, here, is in the use of the rear static load, P_p, rather than total vehicle weight in determining the magnitude of weight transfer which accrues under a deceleration level, in g's, equal to the friction coefficient, f. Another "error" of sorts was also made in the analysis with the use of a design value of "f" equal to 0.8. The use of such a high friction level for accrual of simultaneous front and rear lockup will generally result in the front wheel being overbraked at lower friction levels. The error in the load transfer calculation, however, tended to compensate for the high selected value of f such that the resulting proportioning yields simultaneous lockup at front and rear wheels at about f = 0.4.

Thus, the integral braking system becomes sized in a rather reasonable way, although it might be argued, given the consequences of front-wheel lockup, that even f = 0.4 is somewhat above the desirable level. Further research on the utility of proportioned braking systems for motorcycles appears needed, however, before such judgments can be supported.

In any case, Moto Guzzi's contribution describes the only existing proportioned braking system for motorcycles and provides a detailed description of the design characteristics of that system.

An incidental piece of information was obtained during this study by way of the Los Angeles (California) Police Department (LAPD), which has had a substantial degree of experience with Moto Guzzis in its patrol fleet equipped with integral braking systems. The LAPD has experienced a generally favorable record with these machines and has judged the linked-brake feature a desirable aspect of motorcycle design—although the rider's need for auxiliary front application still remains. While this police fleet experience is carefully couched within the precaution that "A rider must get used to it, first," the general report is positive.

A digest of the contributions provided by the four respondents indicates that a revised motorcycle braking standard should be capable of "accommodating" at least the following major variations in the configuration of motorcycle braking systems:

1) An actuator system incorporating:
    - a) one front and one rear brake actuated by a single foot pedal (with fixed proportioning) and
    - b) one front brake actuated by a hand lever.
2) The above system with antilock control on either the front or both wheels.
3) A conventional, independently-actuated brake system with antilock control on either the front wheel or on both wheels.

Regarding the applicability of a tow-test-based standard to motorcycles with proportioned braking systems, a number of procedural variations are available to account for the feature of "linked" front and rear brakes. Firstly, to conduct a burnish test the distribution of burnish "work" between front and rear brake assemblies can most directly be assured by decoupling the otherwise "linked" systems. For example, in the case of a vehicle configured like the Moto Guzzi system, three brakes need to be burnished, one at the rear and two at the front wheel. In this case, burnishing is achieved by generating the front-only and rear-only tow force levels as specified in Section 4.2, using each front and rear brake in turn. To obtain individual brake applications, the coupled brake elements must be separated. Likewise, in the case of thermal- and water-fade tests, the front and rear systems must be decoupled so that objectively defineable braking inputs can be applied at each wheel.

For effectiveness testing of proportioned, coupled systems, either of two procedures are possible. If the coupled brakes are separated, the limit braking capability of the motorcycle can be assessed through the procedure outlined in Section 3.2. By this approach, limit braking performance is described simply in terms of the brake torque or tire traction level constraint (as has been the basic definition for independently-braked machines). The presence of a coupled brake system (with a supplemental front actuator, and third brake) thus affords no conceptual complication to the basic procedure, although brake decoupling is required.

A second possibility for effectiveness testing involves retaining the proportioned system in its as-designed (coupled) state and employing a sequence of combined front and rear applications up to the tire traction, or brake torque, limits. For example, with the tow height fixed at the height of the center of gravity, the foot pedal could be applied up to a fixed pedal force and then the supplemental front hand lever applied with a ramp input of force up to the condition of wheel lock. Note that as the front hand lever (and thus front brake) is applied, the rear tire load decreases due to load transfer, thus bringing the steady value of rear brake torque closer to that needed for wheel lockup. As the initial steady value of brake pedal force is sequentially increased, a condition will be reached at which the application of the hand lever yields simultaneous front and rear wheel lockup and thus maximum tow force. By this scheme, the limit retardation capability of the proportioned brake system-equipped motorcycle could be assessed without decoupling brake elements.

Going beyond proportioned brake systems, it is clear that by means of the basic tow-test assessment of the limit braking performance of a motorcycle, antilock-equipped cycles are, likewise, easily tested. Using the procedure outlined in Section 3.2, the effectiveness performance of antilock-equipped vehicles is determined on a wheel-by-wheel basis, with the tow force numeric ($FT_{f,r}$) defined as the average value obtained during antilock cycling. To obtain this measure, the tow height is adjusted according to the scheme prescribed for non-antilock systems with hand lever (foot pedal) forces being applied up to either the brake torque or tire traction limits.

The additional, and presumably most important, feature of the antilock system—the slip minimization behavior—remains uncharacterized by this approach. As stated earlier, however, the supposed benefits to controllability must be evaluated on the basis of findings obtained in research which treats the rider-vehicle system.

Aside from the basic improvements or changes considered above, other improvements cited by the manufacturers, such as improved wet traction performance, improved friction materials, improved force delivery efficiency of cables, and the like, do not affect the test methods used by a standard. Nevertheless, the setting of performance requirements in the future will be tied, in some measure, to the absolute braking capabilities of motorcycles—as influenced by the performance characteristics of the various components of cycle braking systems.

5.0 CONCLUDING REMARKS

This study has served to examine the basic methods and supporting rationale applicable to the development of a motorcycle braking performance standard. The study has provided a full-scale trial of the existing standard, FMVSS 122, yielding an assessment of the degree of compliance of contemporary motorcycles as well as an assessment of the adequacy of the written standard as a test procedure.

Conclusions deriving from the test experience gained in the FMVSS 122 test series are:

1) A small sample of motorcycles was found to comply, in general, with the standard.

2) In certain cases, the achievement of a performance level in compliance with the existing standard appears to <u>require</u> a superior level of rider skill.

3) The 122 test procedure is inherently non-objective in all tests in which the distribution of braking effort among the front and rear brakes is left to the discretion of the rider.

4) The 122 procedure is excessively hazardous in conducting stops from speeds above 30 mph, in which the front-wheel traction limit must be approached.

5) The wet brake recovery portion of the standard appears to be fundamentally inadequate as a means of assessing the safety quality of a motorcycle braking system during wet weather conditions.

This study has proceeded from the observations of the shortcomings of FMVSS 122 to develop a new method for measuring motorcycle braking performance. This method serves to objectify the test process, specifying all brake control inputs within a sequence of front-only and rear-only applications. The test procedure not only objectifies the distribution of braking inputs for burnishing and thermal loading applications, it also eliminates the rider skill influence from limit braking measurement. In full-scale tests, this procedure has been found to be practicable and suited to the general scenario of a federal rule on motorcycle braking performance. The developed methodology has also been found adaptable to advanced braking systems such as may be anticipated to evolve within the next ten years in the motorcycle market.

On the basis of the conceptual foundation of the developed methodology, its successful demonstration in full-scale trials and its applicability to future brake systems, the technique is recommended for development into a next-generation motorcycle braking standard. Together with this recommendation, however, must come a specific caution as to a major limitation in the current state of knowledge which tends to place the general value of a motorcycle braking standard in question. This matter concerns the lack of a sound basis for specifying the modulability of the brake system or, put another way, that quality which permits a typical rider to accrue the vehicle's innate stopping capability without suffering wheel lockup and the attendant loss of control. Thus, together with the recommendation that the new test method be incorporated into a revised standard, we likewise recommend that research be conducted to establish the grounds for a motorcycle brake system modulability requirement. Further, it should be noted that a requirement level for a limit stopping capability may have to be adjusted to be compatible with a specification covering the modulation quality of the braking system. Moreover, motorcycle brake systems are seen as meriting a unique methodology for their performance measurement inasmuch as motorcycles, themselves, represent a unique class among motor vehicles. Further, it may be hypothesized that the safe braking of motorcycles depends as much, or more, upon the rider's ability to interact with his machine properly as it does upon the machine's physical limitations in braking performance.

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