

Skid Resistance of Nontangent Sections of Roadways

1980

Texas Transportation Institute

1. Report No. FHWA-RD-80-		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle SKID RESISTANCE OF NONTANGENT SECTIONS OF ROADWAYS				5. Report Date February, 1980	
				6. Performing Organization Code 3871	
7. Author(s) R. D. Tonda and R. A. Zimmer				8. Performing Organization Report No. TTI-ARP-3871-1	
9. Performing Organization Name and Address Texas Transportation Institute Texas A&M University College Station, Texas				10. Work Unit No. (TRAIS) FCP 31W2-014	
				11. Contract or Grant No. Contract DOT-FH-11-9481	
12. Sponsoring Agency Name and Address Federal Highway Administration Office of Research and Development HRS-12 Washington, D. C. 20590				13. Type of Report and Period Covered Interim Report (Phase I) September, 1978- February, 1980	
				14. Sponsoring Agency Code HRS-12	
15. Supplementary Notes FHWA Contract Manager: Glenn Balmer (HRS-12)					
16. Abstract <p>This report presents the results of a detailed literature review and a limited testing program analyzing the various methods of skid resistance measurement and their applicability for use on nontangent sections of roadway. Considerable emphasis is placed on the current ASTM E-274 two-wheel skid trailer. Other techniques evaluated include the Mu-Meter, the one-wheel skid trailer, the British Pendulum Tester, the Diagonal Braked Vehicle and the SAAB Friction Tester.</p> <p>The preliminary analysis indicates that the two-wheel ASTM E-274 skid trailer, with only minor modifications, is a suitable method for nontangent skid resistance measurement. The appropriate modifications are outlined in the text. Additional modifications and design concepts are proposed for the at-speed measurement of highway geometrics which may effect the computed skid number. A test plan for the detailed design, development, construction and full-scale validation testing of a suitably modified trailer is presented as the outline for Phase II of the research effort.</p>					
17. Key Words Skid Resistance, Nontangent Skid Resistance, Skid Number, Highway Safety, Pavement Surface Design, Highway Geometrics, Pavements			18. Distribution Statement No restriction. This document is available through the National Technical Information Service, Springfield, Virginia 22161		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 88	22. Price

PREFACE

This is the first report issued in a two-phase study under DOT Contract FH-11-9481, which deals with "Skid Resistance of Nontangent Sections of Roadways".

This report presents the results of a detailed literature review and a limited testing program evaluating the measured and projected nontangent performance of the currently popular and promising methods of skid resistance measurement.

Recommendations are presented for work to be accomplished in Phase II of the study which efforts will fill gaps revealed by the investigations of Phase I, develop and construct a modified ASTM E-274 two-wheel skid trailer and evaluate its performance, both tangent and nontangent, in considerable detail.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Mr. Glenn Balmer, contract representative of the Federal Highway Administration, for his assistance in securing vital background information for the study and for his counsel and devoted interest in assuring the successful execution of the objectives of the study.

The secretarial and technical staff of the Safety Division is commended for the preparation of the manuscript.

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LIST OF MATHEMATICAL AND SKID RESISTANCE SYMBOLS

A, a	=	Acceleration
b	=	Height of drawbar hitch from level ground
c_{μ}	=	Dry cornering slip number/100
c	=	Distance from drawbar center to trailer c.g. along the length of the trailer
e	=	Distance from center of test wheel contact to c.g. along the length of the trailer
F	=	The towing force parallel to the trailer axis supplied by the tow vehicle at the hitch
F_{ya}	=	Available side force
F_{yd}	=	Side force demand
F_s	=	Side force developed in unlocked wheel due to locking the test wheel
g	=	Acceleration of gravity
H	=	Height of hitch center from ground level
h	=	Height of c.g. from level ground
m	=	Mass acting at trailer c.g.
r	=	The radius of curvature of a nontangent section, measured in a horizontal plane
R	=	The near vertical reaction (support) perpendicular to F and S supplied by the tow vehicle at the hitch
S	=	The side force developed at the tire patch center of the right (unlocked) wheel
S_f	=	The force component parallel and coplaner with S which is developed at the hitch
t	=	The track of the measuring wheels (contact patch to contact patch)
V	=	The instantaneous forward velocity of the trailer

LIST OF SYMBOLS (cont.)

W	=	Dynamic test wheel vertical load
W_a	=	Additional load applied to rolling (unlocked) wheel
W_l	=	Static test wheel vertical load
W_r	=	Static weight supported by the rolling (unlocked) wheel
W_t	=	Total static test trailer weight
Y_L	=	The near vertical reaction force supplied by the pavement at the center of the tire patch of the left (locked) wheel
Y_R	=	The near vertical reaction force supplied by the pavement at the center of the tire patch of the right (unlocked) wheel
θ	=	The angle of super elevation (positive is upwards to trailer right)
μ	=	The (wet) dynamic coefficient of friction
ϕ	=	The angle of grade (positive is uphill)
SN_v	=	Skid Number obtained by method E-274 at speed v
MuN	=	Mu Number obtained using standard Mu-Meter techniques
SDN	=	Stopping Distance Number obtained from DBV tests

I. INTRODUCTION

The following report was prepared under the sponsorship of the Office of Research, Structures and Applied Mechanics Division, of the Federal Highway Administration. Mr. Glenn Balmer of this office served as the technical contract manager for the project, and much credit is due his advice and counsel during the course of the study.

The project began with a thorough literature review of domestic and foreign papers and study reports. The primary object of the review was to identify those sources which discuss the measurement of skid resistance of nontangent (some not straight and some not level) sections of roadway. In depth review of over sixty titles uncovered only five reports that even mention nontangent measurement, and these citations are brief and uninformative.

An alternate function of the literature review was to provide background information to be used later in the study evaluations. In this respect, several of the reviews identified papers which were invaluable later in the study. This aspect was especially useful since Phase I of the project, which is the subject of this report, was not structured and did not allow for large scale physical testing of the various measurement methodologies. Therefore, many of the evaluations and recommendations of this report are based on a limited testing program combined with detailed study of the literature as identified early in the project. These references were especially valuable in determining cost figures, tangent behavior characteristics, maintenance requirements, and other evaluation criteria used in analyzing the several methods examined.

It is not considered a difficulty in the present study that more physical testing was not done. The purpose of the Phase I portion of the study was to identify the most promising measurement method or methods to be developed, "fine-tuned", and validated in Phase II. The last chapter of this report indicate the authors' recommendations for an extensive physical testing program to validate the proposed measurement technique, and it is only during an evaluation of that type that the true value of the technique can be identified. Hence, it is during the Phase II effort that the major experimental effort will be expended.

Certainly the most gratifying result of the study thus far is the satisfactory performance of the popular two-wheel ASTM E-274 trailer. Such a result implies the effective utilization of a large capital investment by the various states. It also negates the necessity for additional large investment in a time of ever-tightening budgets. At the conclusion of the Phase II study, we should be in possession of a documented, cost-effective method for the measurement of skid resistance of nontangent sections of roadway which is compatible with our current methods of tangent measurement and can be implemented with short time delays.

II. CAPABILITIES AND LIMITATIONS OF THE TWO-WHEEL ASTM E-274 SKID TRAILER

This chapter discusses the capabilities and limitations of an unmodified two-wheel ASTM (American Society for Testing and Materials) E-274 type trailer used for the measurement of skid resistance. These characteristics were determined by evaluating the literature which was reviewed early in the project, developing and analyzing analytical expressions which predict the forces on the trailer during measurement, and by a limited testing program which was used to validate the analytical expressions and to identify those limitations which the analytical approach could not address. This chapter also proposes methods for overcoming or extending the limitations identified. These methods are examined later in the report when recommendations for nontangent measurement are developed.

Development of Analytical Expressions

In 1971, the National Bureau of Standards commissioned a study of the dynamic behavior of the ASTM E-274 type trailer (6). The resulting report was one of the first (and only traceable) documents which attempted a theoretical analysis of the characteristics of such trailers. The techniques presented in the referenced report are relatively sophisticated and require detailed knowledge of trailer characteristics such as mass moments of inertia and tire spring and damping constants. The results presented in the paper do not appear to be based on a sufficient experimental sampling to draw any valid conclusions and the authors justifiably avoid doing so.

The most interesting conclusion which is drawn in this report is that the initial transient behavior of the trailer is essentially stable after about three to four seconds of locked wheel operation. Of course, those operators of E-274 trailers are aware of this fact and recorder traces of trailer output exhibit ample support to the statement. The equations developed in this report, although useful, do not attempt to answer the fundamental questions regarding performance of the trailer in the equilibrium measurement mode since, as the authors state, they were developed primarily to identify roll, pitch, and vertical motion.

Because of the objections and limitations cited above, it was necessary to develop a set of governing equations based on the equilibrium of forces on the trailer when the trailer was in the locked-wheel measurement mode. We begin this derivation by drawing free-body diagrams of the trailer on an upward (positive) grade and with an arbitrary cross-slope (superelevation). These free-body diagrams are illustrated in Figures 1 and 2. Note that consideration has been made for a centrifugal force acting on the center of gravity (c.g.) of the trailer which is proportional to V^2/r . This term accounts for loads induced due to the nontangent operation of the trailer as encountered in a curve.

We begin our analysis by summing forces in the x-direction of Figure 1.

$$F - \mu Y_L - mg \sin\theta \cos\phi - \frac{mV^2}{r} \sin\theta \sin\phi = ma.$$

Summing forces in the z-direction we find

$$2N + R - mg \cos\theta \cos\phi - \frac{mV^2}{r} \sin\theta \cos\phi = 0.$$

And completing our analysis of Figure 1, we sum moments about the c.g. of the trailer.

$$2N(e) + \mu Y_L(h) + F(b-h) - R(c) = 0.$$

Similar analysis of the two diagrams in Figure 2 yield the balance of the equations necessary to specify the forces acting on the trailer. The resulting expressions can be reduced to six equations identifying the six unknown forces acting on the trailer at equilibrium, as follows:

$$(1) \quad F - \mu Y_L = mg \cos\theta \sin\phi + \frac{mV^2}{r} \sin\theta \sin\phi.$$

$$(2) \quad R + Y_L + Y_R \cos\theta = mg \cos\theta \cos\phi + \frac{mV^2}{r} \sin\theta \cos\phi.$$

$$(3) \quad Rc + F(h-b) - Y_R e \cos\theta - Y_L(\mu h + e) = 0.$$

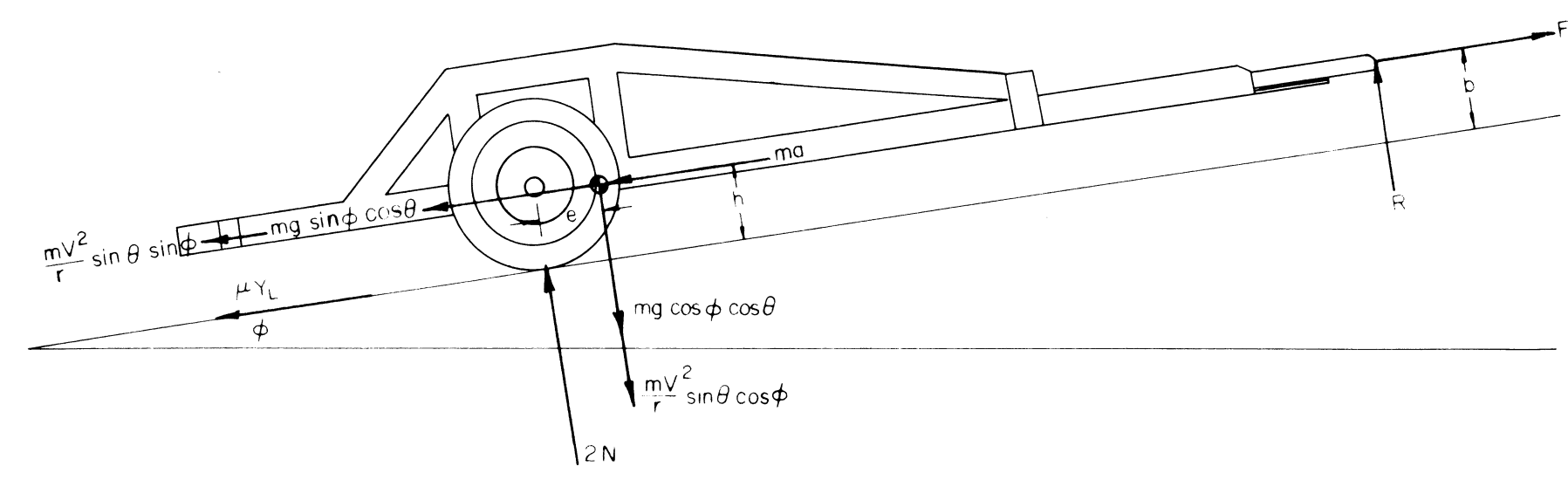
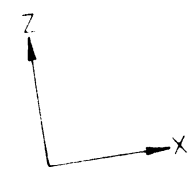
$$(4) \quad S - S_f - Y_R \sin\theta = \frac{mV^2}{r} \cos\theta - mg \sin\theta.$$

$$(5) \quad Y_L(\mu t/2) + Y_R e \sin\theta - S e - S_f c = 0.$$

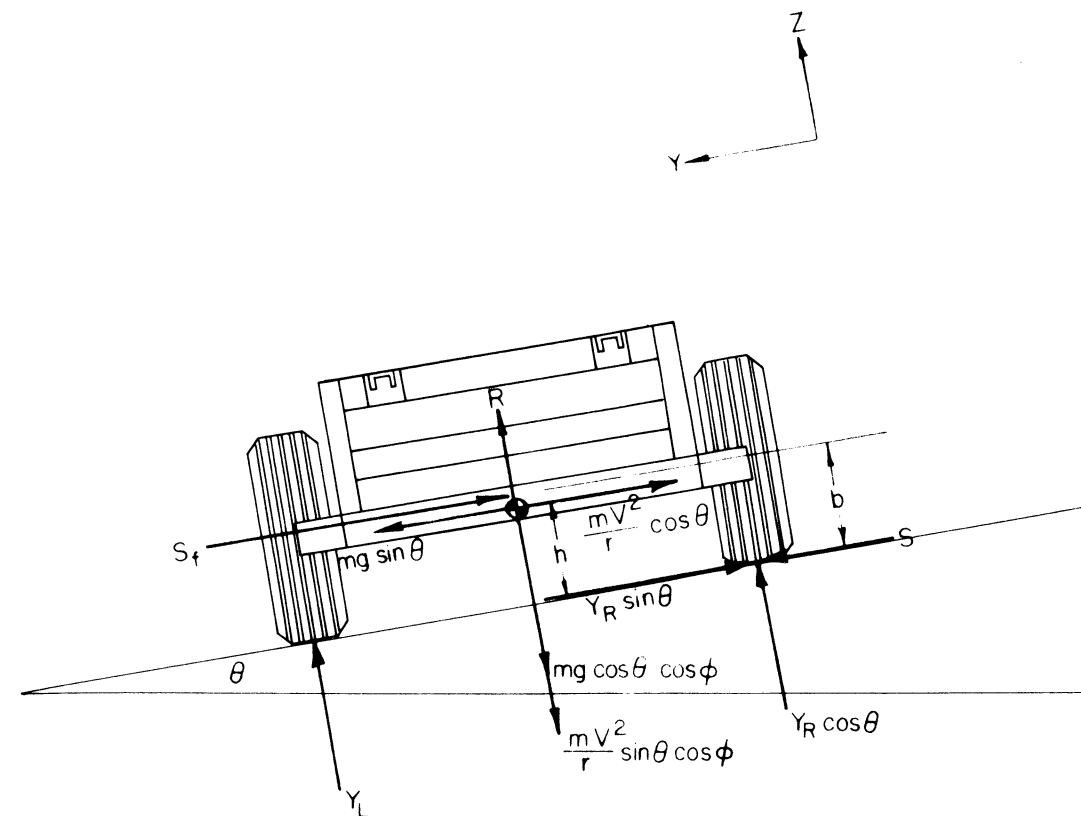
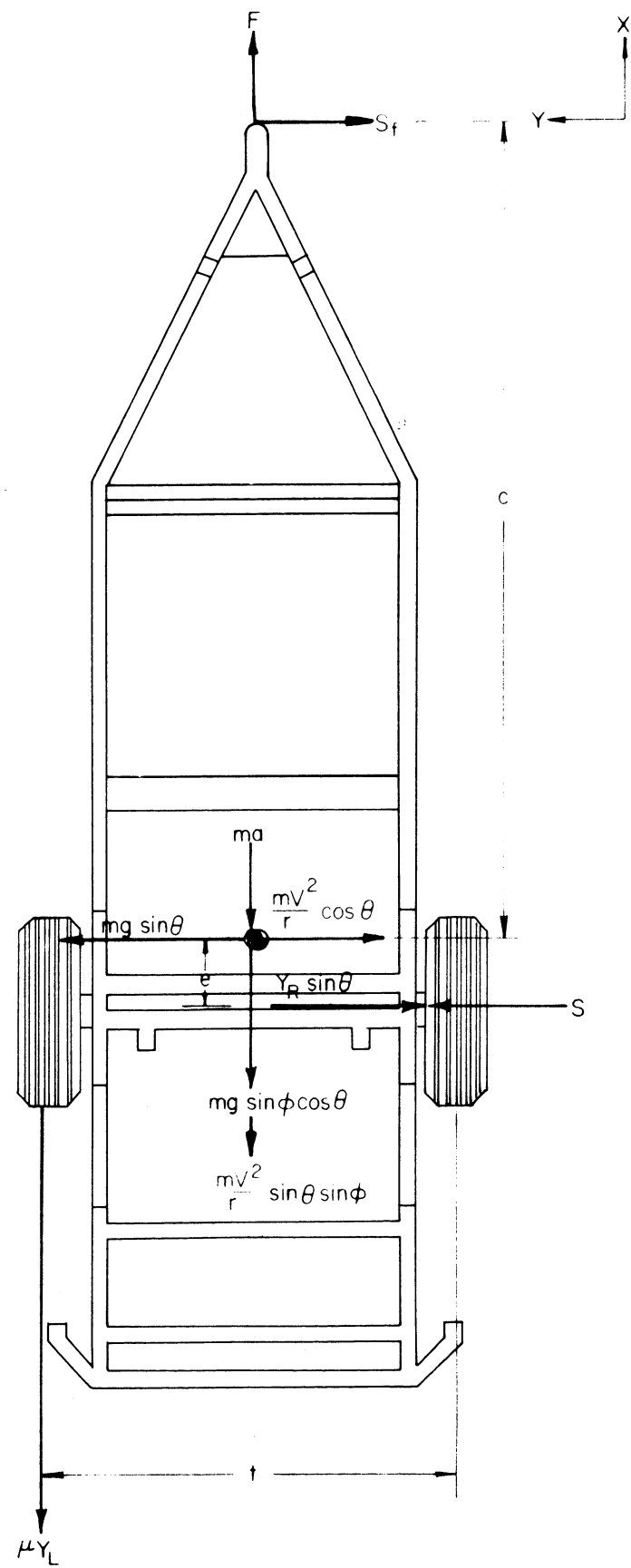
$$(6) \quad Y_R(t/2 \cos\theta + h \sin\theta) - Y_L(t/2) - S h + S_f(h-b) = 0.$$

It should be noted that the following assumptions were made in deriving equations 1-6.

- i) The locked wheel of the trailer (in this case, the left wheel) does not develop any out of plane forces, i.e., does not experience any side force.
- ii) The trailer is in equilibrium at some constant velocity V , i.e., the acceleration (a) is zero.
- iii) The compression or extension of the trailer and tow vehicle suspension is negligible at equilibrium; i.e., the static trailer dimensions are good approximations of the trailer characteristics at dynamic equilibrium.



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We now have equations 1-6 determining the equilibrium values of the following six forces:

- F - The towing force parallel to the trailer axis supplied by the tow vehicle at the hitch.
- R - The near vertical reaction (support) perpendicular to F supplied by the tow vehicle at the hitch.
- Y_L - The near vertical reaction force supplied by the pavement at the center of the tire patch of the left (locked) wheel.
- Y_R - The near vertical reaction force supplied by the pavement at the center of the tire patch of the right (un-locked) wheel.
- S - The side force developed at the tire patch center of the right (un-locked) wheel.
- S_f - The force component parallel to S which is developed at the hitch.

A computer program was developed to solve these equations using the technique of Gaussian elimination. A listing of this program is shown in Appendix I of this report, and a sample output for the TTI Highway Friction and Hydroplane trailer operating in the tangent mode is shown in Figure 3. Other examples of the use of this program can be found in the balance of this report.

SKID TRAILER DIMENSIONS:

M=1060.5 kg (6.06 lb-sec**2/in) H=0.3175 m (12.50 in)
B=0.3048 m (12.00 in) T=1.5400 m (60.63 in)
C=2.8435 m (111.95 in) E=0.2235 m (8.80 in)

DATA SET # 1

CROSS-SLOPE ANGLE (THETA)= 0.00 degrees
VERTICAL SLOPE ANGLE (PHI)= 0.00 degrees
COEFFICIENT OF FRICTION (MU)= 0.440
RADIUS = -67.1 m (-220.0 ft) (+ R.H. CURVE)
VEHICLE VELOCITY = 48.3 km/h (30.0 mph)

VARIABLE OUTPUT

F = 2259.4 N (508.0 lb)
Y(R)= 4280.6 N (962.4 lb)
Y(L)= 5146.6 N (1157.1 lb)
S = -2069.4 N (-465.2 lb)
S(F)= 775.9 N (174.4 lb)
R = 983.8 N (221.2 lb)

DATA SET # 2

CROSS-SLOPE ANGLE (THETA)= 6.84 degrees
VERTICAL SLOPE ANGLE (PHI)= 0.00 degrees
COEFFICIENT OF FRICTION (MU)= 0.440
RADIUS = -67.1 m (-220.0 ft) (+ R.H. CURVE)
VEHICLE VELOCITY = 48.3 km/h (30.0 mph)

VARIABLE OUTPUT

F = 2277.9 N (512.1 lb)
Y(R)= 3884.5 N (873.3 lb)
Y(L)= 5188.8 N (1166.6 lb)
S = -2733.2 N (-614.5 lb)
S(F)= 869.4 N (195.5 lb)
R = 955.7 N (214.9 lb)

Figure 3. Sample Output of Analytical Program.

Testing Program

A limited series of tests were conducted on an E-274 type trailer (TTI's Highway Friction and Hydroplane Research Trailer). The program was aimed at achieving the following two goals:

- i) Establishing the validity and accuracy of the analytical expressions developed in the previous section, and
- ii) Approaching and confirming the limiting performance characteristics of this particular E-274 trailer and establishing limit characteristics which are not suitable for analytical evaluation.

In the discussions which follow, several factors which limit the performance arena for the E-274 trailer are identified. Many of the values of these parameters far exceed the recommended or even remotely conceivable design value for that parameter in the real world. In such cases we have attempted to identify the recommended or reasonable extreme, and demonstrate, either through testing or analytical evaluation, that such configurations are well within the realm of operation of the E-274 trailer.

Distance (Length) Limitations

It is a weakness inherent in the ASTM E-274 type trailer that measurement of skid resistance be conducted at some speed; usually 65 km/h (40 mph). The weakness of this measurement scheme becomes apparent when an attempt is made to make skid measurements near T-type intersections. Roadway configurations similar to those shown in Figure 4 are examples of relatively common intersections which present a measurement problem to the E-274 trailer.

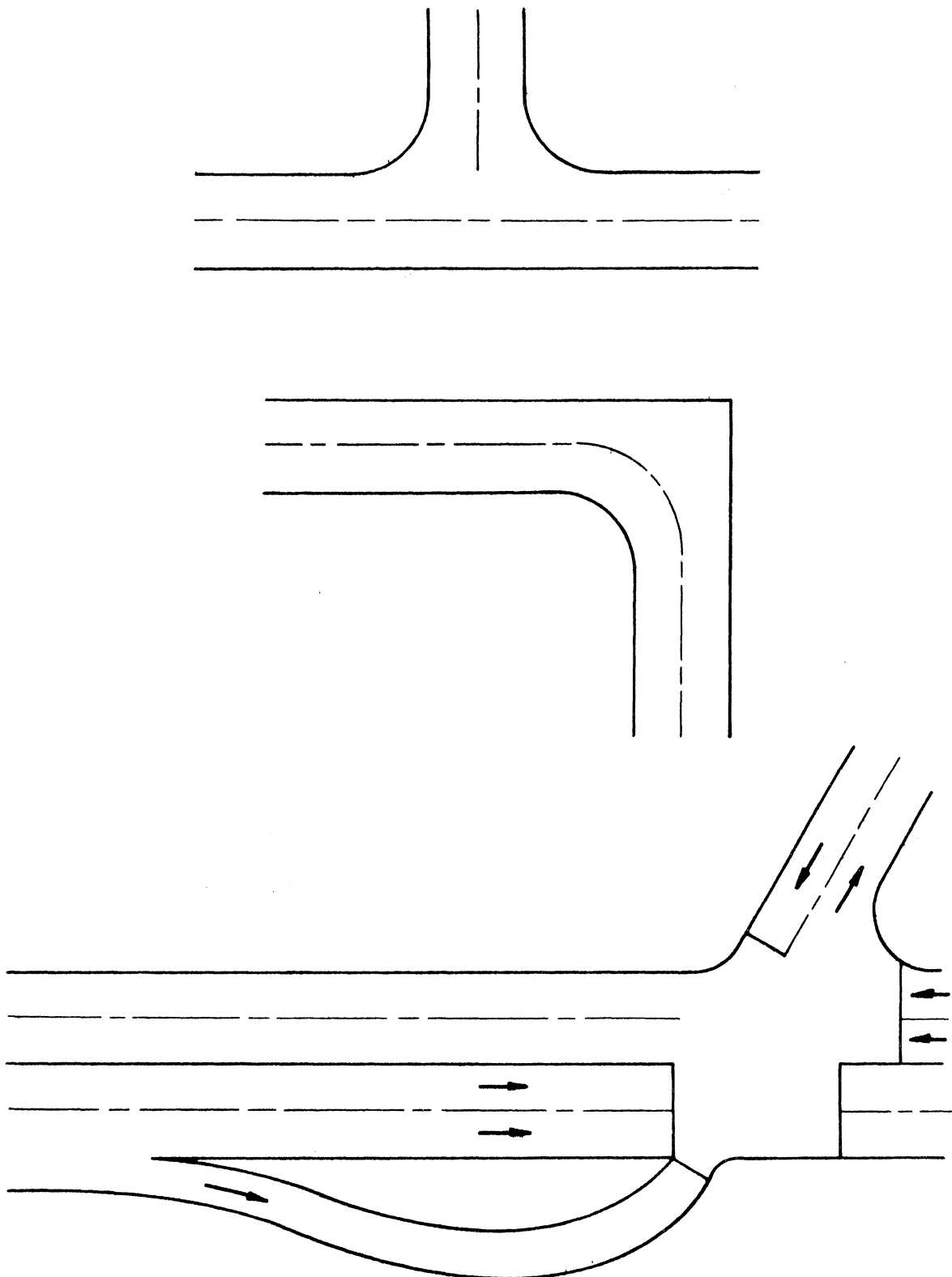


Figure-4. Roadway Configurations Which Present Length Limitations to the E-274 Trailer.

In order to quantify the limitations of the E-274 trailer in this measurement mode, physical tests were conducted at the Texas A&M Research and Extension Center on the asphalt handling surface. A worst case T-type intersection was laid out near the center of the pad so that some extreme braking and acceleration maneuvers could be executed with ample recovery area for safety of the driver and equipment. The dimensions of the test area were obtained from AASHTO minimum design requirements (1,2) and are outlined in Figure 5.

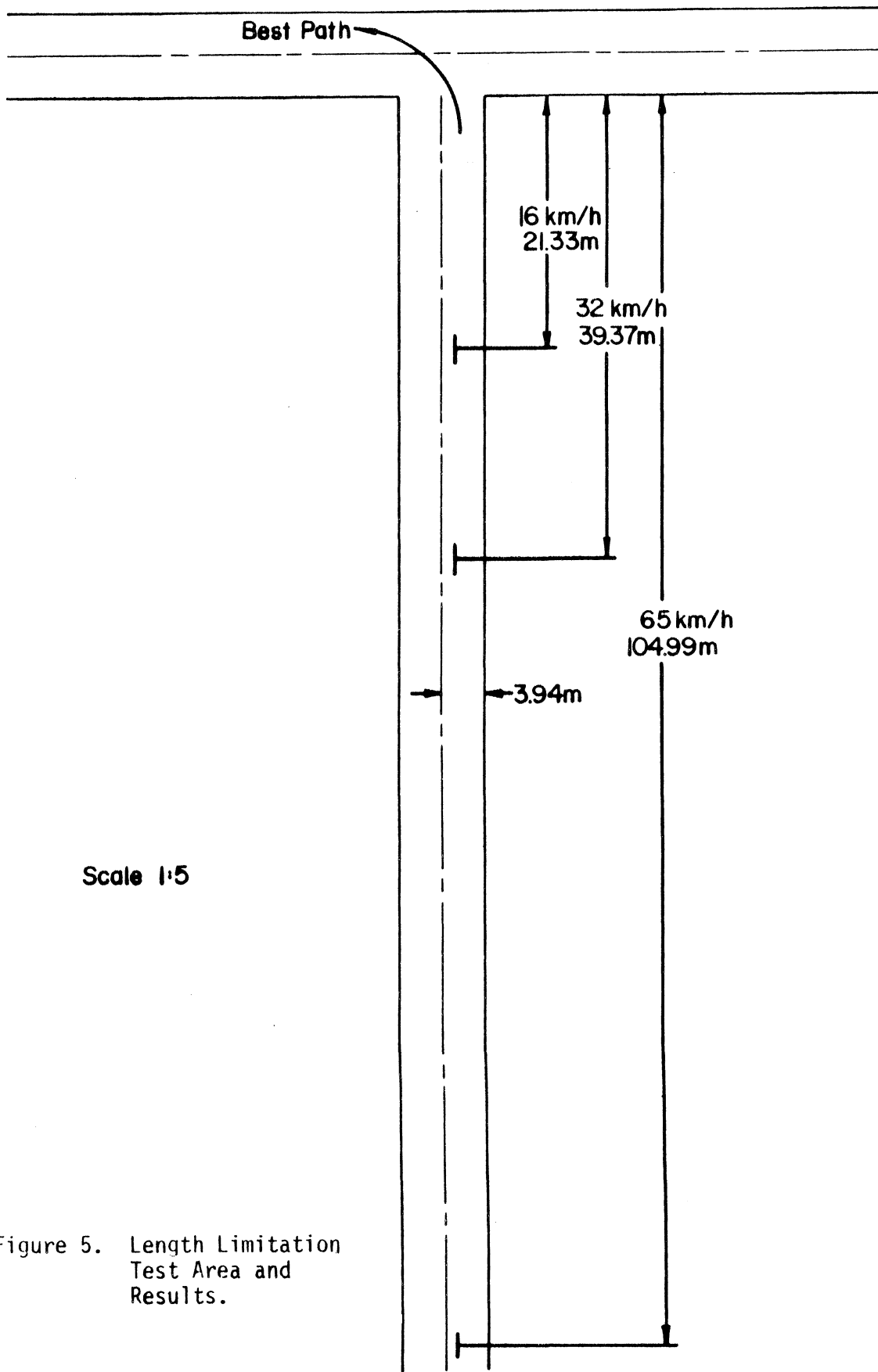
Results of the test program are shown in Table 1, and the minimum dimensions are identified in Figure 5. The test program indicated that accurate, repeatable skid resistance values can be obtained safely at distances exceeding 105 m from the intersection for an SN_{65} and at distances over 40 m for an SN_{32} .

Grade Limitations

Examination of the free body diagrams in Figures 1 and 2 clearly shows that grade influences only the draw bar force on the trailer. Further analysis of the equations of trailer behavior previously developed supports this observation, and also establishes that if an E-274 trailer is measuring skid resistance from the ratio of locked-wheel vertical and drag forces, the grade influence will have an insignificant effect on the computed skid number.

Curvature Limitations

Considerable attention was given to the situation of the E-274 trailer in a curve due to the potentially high centrifugal forces acting on the mass-center of the trailer. This study was broken down into



Scale 1:5

Figure 5. Length Limitation Test Area and Results.

Table 1. Results of the Test Program

SPEED	DISTANCE REQUIRED TO OBTAIN REPEATABLE CORRECT SKID NUMBER (FROM "T" INTERSECTION)	MEAN SN
16 km/h (10 mph)	21.3m (65 ft)	51.2
32 km/h (20 mph)	39.4m (120 ft)	46.6
65 km/h (40 mph)	105.0m (320 ft)	42.4

In normal, tangent operation on the same section of this particular skid pad, the following skid resistance values were obtained.

$$SN_{16} = 51$$

$$SN_{32} = 46$$

$$SN_{65} = 43$$

two areas of investigation. The first is the introduction of errors into the skid number data due to these forces. The second is one of stability or safety for the equipment and personnel.

The investigation of error producing factors involved both mathematical and test track evaluations of the E-274 system with various levels of side force. By the nature of their derivation, the mathematical expressions predict that measurement of horizontal and vertical forces at the locked wheel will be theoretically error-free, even in curves of extreme degree.

The test-track program involved three homogeneous test surfaces which were the aforementioned asphalt test pad, a concrete pad, and a jennite test pad, all being flat. Two E-274 systems were involved in the study, the T.T.I. Research Test Trailer configured to E-274 specifications, and the FHWA ARSMS*. On the test pads, curves were delineated on the surface with radii of 107 metres and 162 metres. These curves were chosen to produce 0.3 and 0.2 g's respectively at 65 km/h. The lateral acceleration could then be varied by adjusting the speed through the curve. It was found, as will be discussed later, that the safe limit of the system is approximately 0.33 g, and no measurements were attempted above this limit. Both systems measured both dynamic horizontal and vertical forces and calculated SN by means of an analog computer. Figure 6 shows the results of the testing on asphalt with each data point being the average of six runs. The overall ± 2 standard deviation points are indicated along with the ± 5 SN points. Similar

*ARSMS - Area Reference Standard Measurement System

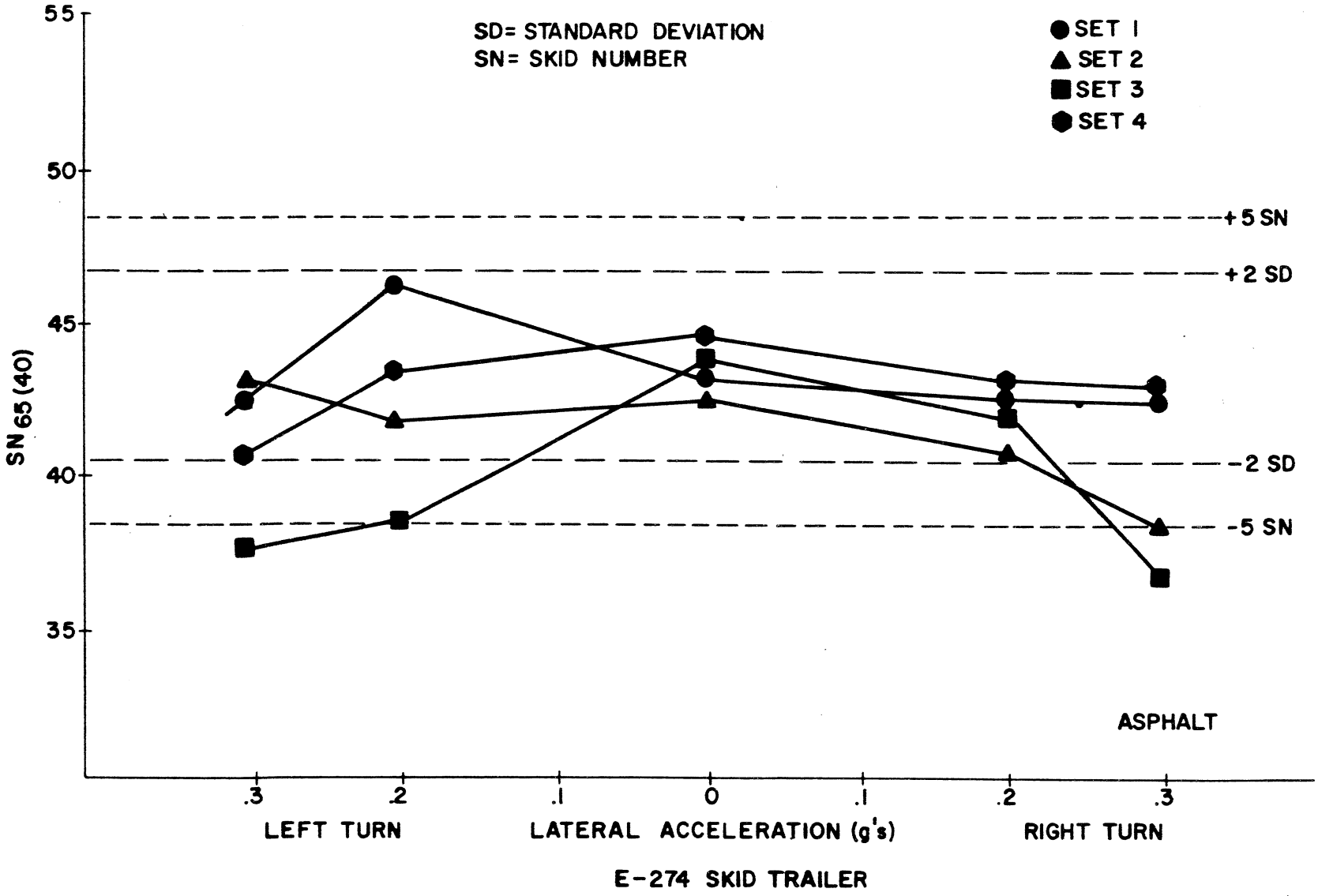


Figure 6. Curvature Effects on Asphalt Pavement.

data are presented in Figure 7 and Figure 8 on concrete and asphalt flush seal (jennite). The apparent slight decrease in skid number at the higher g levels in Figure 6, although perhaps not statistically significant, needs further investigation along with more track testing which will be conducted in Phase II.

Mathematical evaluation of the E-274 system with respect to error producing conditions showed, as mentioned previously, that if both horizontal and vertical measurements of force are made at the locked wheel, theoretically no error will be introduced by even extreme curvature. The measurements of real trailer behavior tend to support this notion. It is important to note however, that the transducers used to measure these forces indicate valid, repeatable results over only a portion of their full operating range. A given trailer-transducer combination could best be evaluated by first determining the valid range for each transducer channel and from this computing a valid range for the computed skid number. Then a series of extreme conditions could be construed and analyzed, using the previously developed simulation for example, and the predicted force values compared to the valid ranges. In the case of the TTI Research trailer however, this approach was fruitless, since instability of the trailer occurred long before even a 5 percent predicted error was encountered. For this reason, it is not anticipated that the above approach would, in general, be useful.

The stability or instability of the E-274 system in a curve is directly associated with the lateral acceleration acting on the c.g. of

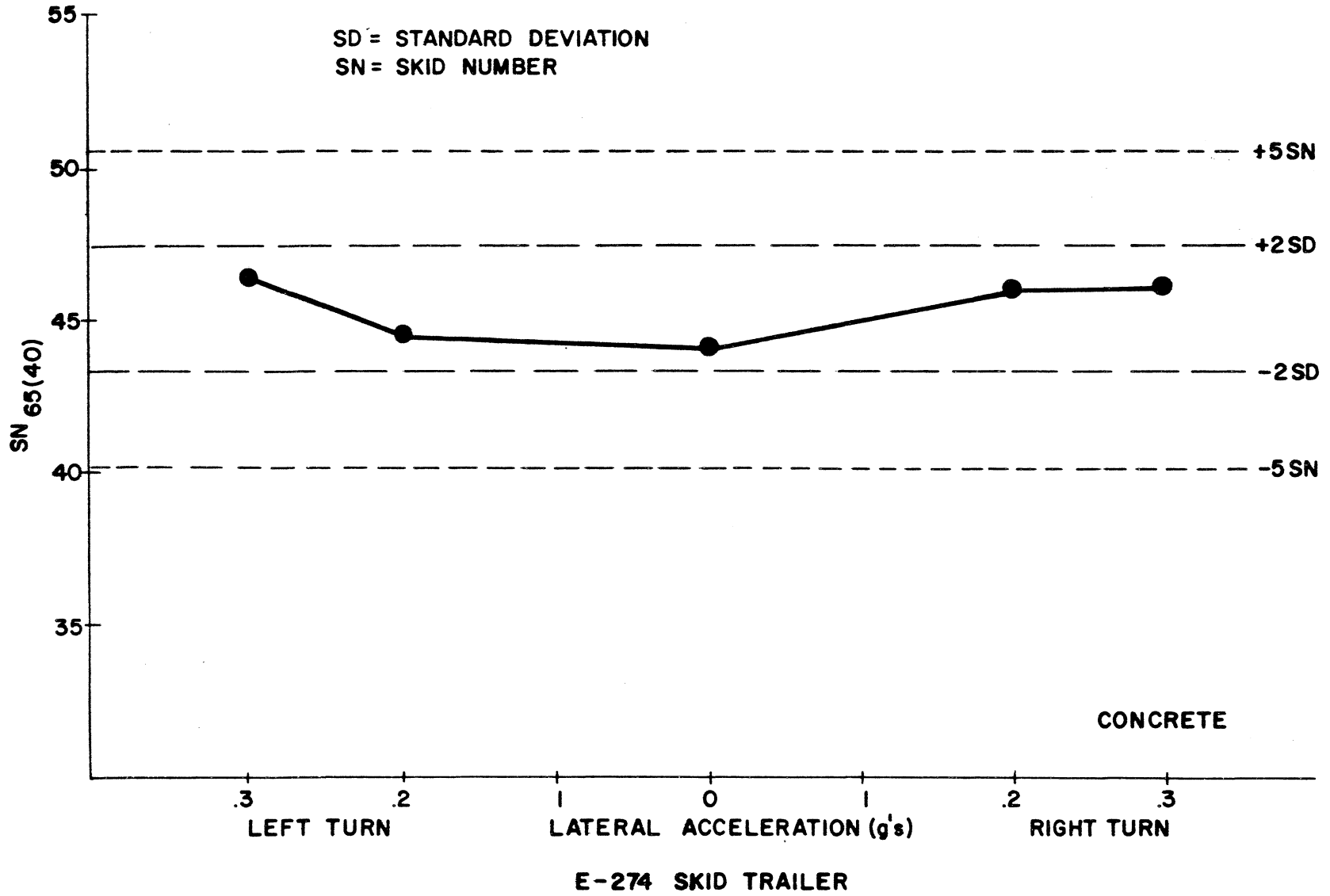


Figure 7. Curvature Effects on Concrete.

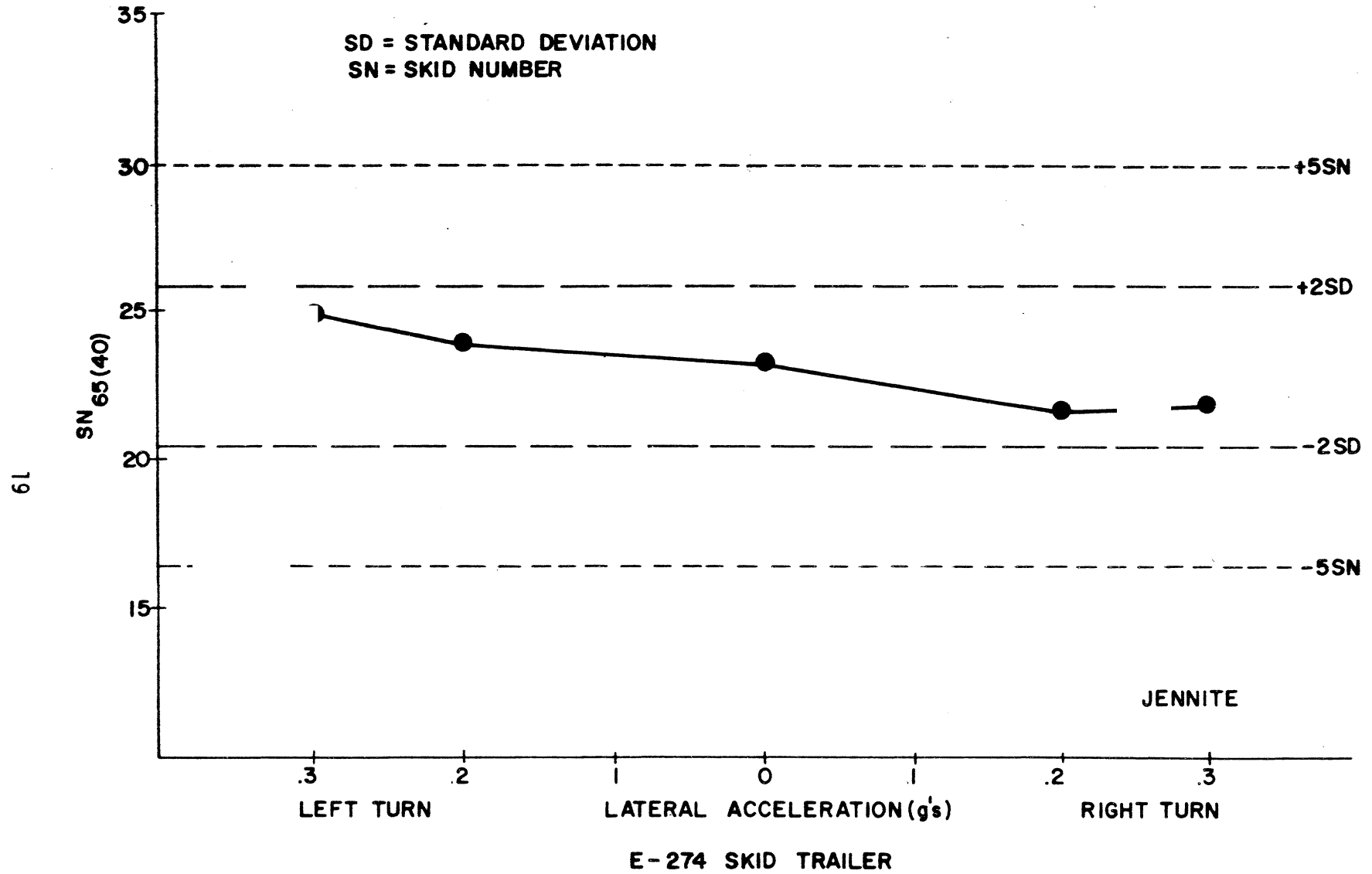


Figure 8. Curvature Effects on Jennite.

the trailer in a curve which creates a need for the unlocked wheel to develop additional, and often considerable, side force. With a given radius and velocity, a flat curve (no superelevation), will produce a greater lateral acceleration than if the proper positive superelevation is used (a severe case condition, more severe than the AASHTO design standards) which is the case in the TTI test pads. This severe case approach was used because it is a very repeatable condition and the large pad area allowed ample recovery room in the event of a spin out. Obviously, a negative superelevation would be an even worse case, but also a highly improbable one. To investigate the amount of articulation angle change that occurred during the locked wheel, non-tangent measurement, a rotational potentiometer was attached between the tow vehicle and the test trailer by means of a flexible shaft. This configuration allowed measurements in the yaw plane only. The output of the transducer was conditioned and placed on a strip chart recorder for evaluation. This measurement also acted as an indicator of incipient slip out to the vehicle driver.

An example output from this measurement is shown in Table 2 under the column Art. Ang. These figures represent the difference between the steady state turn, unlocked and locked conditions. It may be noted that an angular shift occurs even in a tangent or 'TAN' lockup. This is due to the aligning moment produced as the test wheel exhibits drag force. The asterisk (*) shows a condition in which the articulation angle never stabilized but continued to slowly increase during the interval of lockup. To further investigate the effect of lateral force on the system a special rim, for the free rolling wheel, was machined.

Table 2. Curvature Testing Results.

	TTI RUN #1		TTI RUN #2		ARSMS #1
	SKID NO.	ART. ANG	SKID NO.	ART. ANG.	SKID NO.
RIGHT TURN AREA -TAN.	43.1 $\sigma = 2.10$	+0.5°	41.6 $\sigma = 1.90$	+0.3°	44.5 $\sigma = 1.01$
LEFT TURN AREA - TAN	42.5 $\sigma = 1.72$	+0.4°	42.9 $\sigma = 1.26$	+0.4°	42.4 $\sigma = 1.61$
LEFT TURN 40 MPH RADIUS = 162 m (533') 0.20g	46.3 $\sigma = 0.91$	+1.2°	41.8 $\sigma = 1.85$	+1.4°	38.5 $\sigma = 1.08$
RIGHT TURN 40 MPH RADIUS = 162 m (533') 0.20g	44.5 $\sigma = 1.03$	0.0°	40.9 $\sigma = 1.88$	0.0°	42.0 $\sigma = 1.65$
LEFT TURN 36 MPH RADIUS = 107 m (350') 0.25g	44.5 $\sigma = 1.58$	+1.7°	41.9 $\sigma = 1.67$	+1.5°	41.9 $\sigma = 1.52$
RIGHT TURN 36 MPH RADIUS = 107 m (350') 0.25g	38.0 $\sigma = 2.13$	-0.3°	39.1 $\sigma = 2.36$	+0.2°	39.1 $\sigma = 1.44$
LEFT TURN 40 MPH RADIUS = 107 m (350') 0.30g	46.3 $\sigma = 0.86$	+2.6°	40.3 $\sigma = 3.24$	+2.2°	37.7 $\sigma = 1.12$
RIGHT TURN 40 MPH RADIUS = 107 m (350') 0.30g	42.4 $\sigma = 0.68$	*-5.0°	38.2 $\sigma = 0.77$	-0.6°	36.7 $\sigma = 1.27$

Each condition consists of 6 runs.

*No equilibrium reached, articulation angle continued to increase during lockup.

This rim was designed to allow a certain amount of bending in the web due to side force. The web was then strain gaged in one spot so that the strain converted to force could be accurately read at one point, each revolution. This transducer then allowed direct side force measurements during a locked-wheel test in a curve. A typical output from this device is shown in Figure 9. As anticipated the side force capability provided by the test wheel, as it is locked, disappears and must be absorbed by the rolling wheel. In this condition the rolling wheel must provide effectively all the side force necessary to counteract the demand placed on the trailer. It was found that if the available side force is exceeded by the demand, the system will be unstable and yaw or spin out. It was discovered that this unstable condition occurs at approximately half the side force level during a locked wheel test as would occur if both wheels were rolling. This is the condition that limits the trailer, in a locked-wheel condition, to a lateral acceleration of about 0.33 g on a dry roadway that has a cornering slip number of 70. These numbers are based on an average E-274 trailer which should vary only slightly from one trailer to another, since similar weight configurations are required in order to maintain proper calibration.

A comparison of demand versus availability of side friction is shown in Figure 10 at various levels of lateral acceleration. It should be noted that the aligning moment developed by the locked wheel produces a side force in the tangent or "zero g" condition displaces the position of the demand curves, depending on the direction of turn. This critical level of lateral acceleration has been compared to various highway

Right Wheel Side Force
Left Turn - 65 km/h (40 mph), 107 m (350 ft) Radius

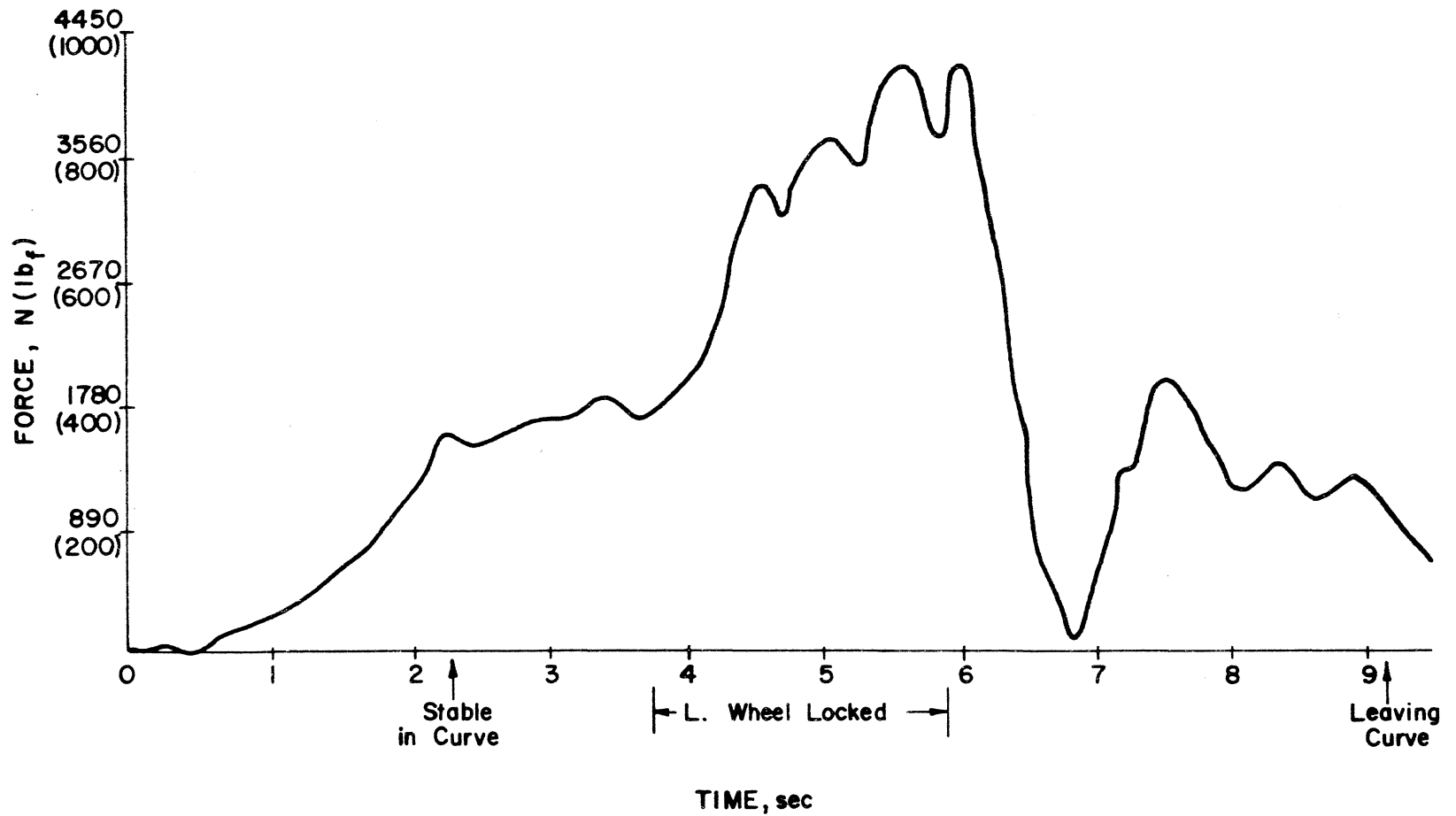


Figure 9. Side Force Transducer Output.

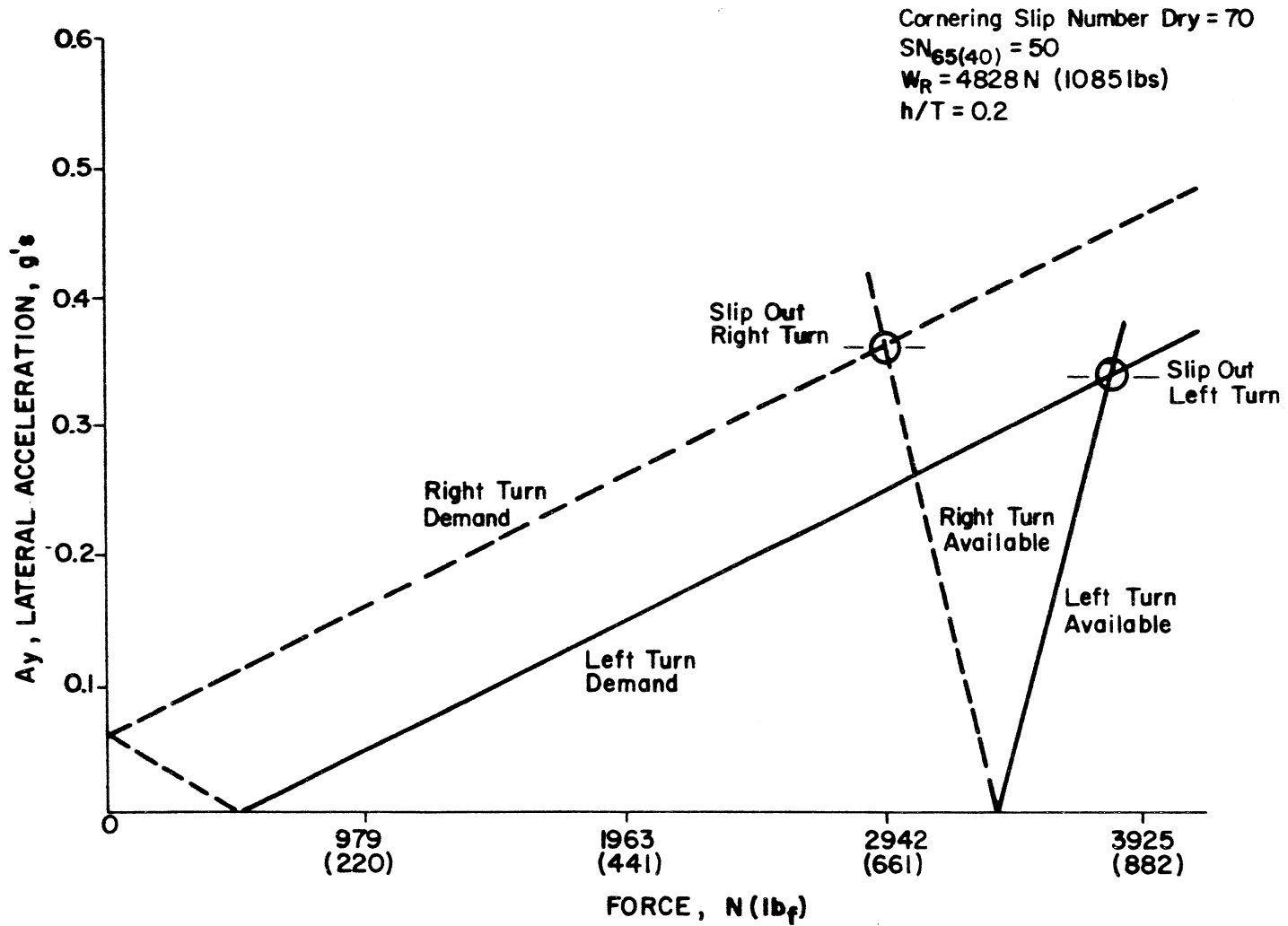


Figure 10. Demand vs. Available Side Force.

design criterion as defined by AASHTO (1), (2). This comparison indicates that if these design practices are followed, one should be able to make SN_{65} measurements on any section of rural highway, except at intersections, including those curves posted 48 km/h (30 mph) in both a safe and accurate manner.

On urban highways the expected frequency of sections which could not be safely measured at 65 km/h would represent a small, but significant portion of the roadway encountered. Though minor in terms of the total mileage of urban highway, these sections may be quite significant in representing the portions of our highway system where accidents occur. After considerable discussion and analysis, three methods for overcoming this difficulty presented themselves:

- 1) Physical modification of the trailer to allow it to develop more side force,
- 2) Procedural modifications which would allow determination of an SN_{65} by other than standard techniques, or
- 3) Procedural modifications whereby skid resistance measurements would be made at posted (design) speeds.

These three options are discussed on the following pages in light of all the previous limitations we have discussed.

Physical Modifications

Analysis indicated no physical modification which would extend the safe limitation of the E-274 trailer in a T-type or other type of length-limited situation. As noted earlier, the limiting factor here is adequate space in which to maneuver, not the maneuvering capability of the tow-vehicle trailer combination. In a similar manner, and as previously

discussed, it can easily be argued that no physical modifications are necessary to compensate for the effect of grade, since the grade effects are negligible.

The real problem area with the E-274 trailer is assuring that it can develop the appropriate level of side force to assure stability. Several approaches were considered, but by far the most promising technique is the addition of a trailing wheel. Such a wheel could be as simple as a damped, hinged frame, pinned to the back of the trailer with the tire rigidly positioned in the frame so that the tire contact patch and the weight on the tire are adjusted to enhance the trailer's overall side force capacity. Conversely, this trailing wheel could be so sophisticated as to make use of an electronic servo-control circuit which would adjust the yaw of the tire to maximize the side force capability with a minimum of additional weight. Both of these approaches could be made to work, but it will be established later that they represent unnecessary extremes.

The following advantages and disadvantages of these approaches should be noted at this time:

- 1) The mechanical modifications would be relatively simple, and could be made on virtually any E-274 type trailer,
- 2) Not a great deal of mechanical advantage would be required to include all properly designed rural and urban highways in the range of the E-274, however,
- 3) It has already been noted that these unmeasurable sections are few in number to begin with, and
- 4) These modifications would almost certainly require a more sophisticated calibration technique.

These concepts will be weighed carefully against similar statements concerning other approaches and techniques in the next two chapters.

Procedural Modifications

Early in the study it was determined that the goal in making non-tangent measurements was to achieve a reliable, repeatable, straight-forward technique. Because of our country's vast data bank and experience with the popular SN_{65} , it seems reasonable to assume that an approach which measures the skid resistance at 65 km/h, thereby directly computing an SN_{65} , would be the most desirable. Another approach would be to make measurements at some other speed(s), perhaps in conjunction with another type of measurement, and through some manipulatory technique, compute the SN_{65} . A third approach, would be to make measurements at some speed other than 65 km/h, such as traffic or posted speeds and report the skid number with a subscript.

The physical modifications identified in the previous section reflect an attempt to reach the ideal criteria mentioned first above. It should be noted that in practice this can probably never be done. The at speed requirement of measuring the SN_{65} directly indicates the virtually impossibility of making the measurement within two meters of a tee intersection. The procedural modifications proposed in this section will explain an attempt to address the second criteria identified above, and to "fill-in" those few sections which the physical modifications could not measure. The next section outlines the less desirable approach of measuring and reporting skid resistance at various speeds.

The most logical procedural modification would be to make measurements on the nontangent section at speeds as close to 65 km/h as possible. A measurement could then be made at some lower speed and a plot of the test results developed. This graph could then be linearly extrapolated to predict a value of the SN_{65} . A graphical representation of this approach is shown in Figure 11. Alternatively, more elegant methods of non-linear extrapolation could be developed making use of more data points or some knowledge of the skid number gradient. These approaches, although more appealing, would likely be more costly and time-consuming, whereas the former, more simplistic approach could be accomplished on site with nothing more than a straight-edge, pencil, and previously prepared graph paper. Another procedural modification which holds some promise would choose some convenient speed and then correct that value to an equivalent SN_{65} , via some analytical procedure. Both of these approaches are evaluated in the next two chapters.

Procedural Modifications (Posted Speed)

A final approach which could be used to measure the skid resistance of nontangent sections is to measure the skid number at the posted or design speed for the section. In this manner, one would report an SN_{32} for example, and determine pavement characteristics by some technique not now commonly employed. This approach would likely use some evaluation methodology similar to that described in NCHRP Report 14, entitled "Skid Resistance" (9) on page 10, and in NCHRP Report 37 (4) by Kummer and Meyer, on pages 51 through 55.

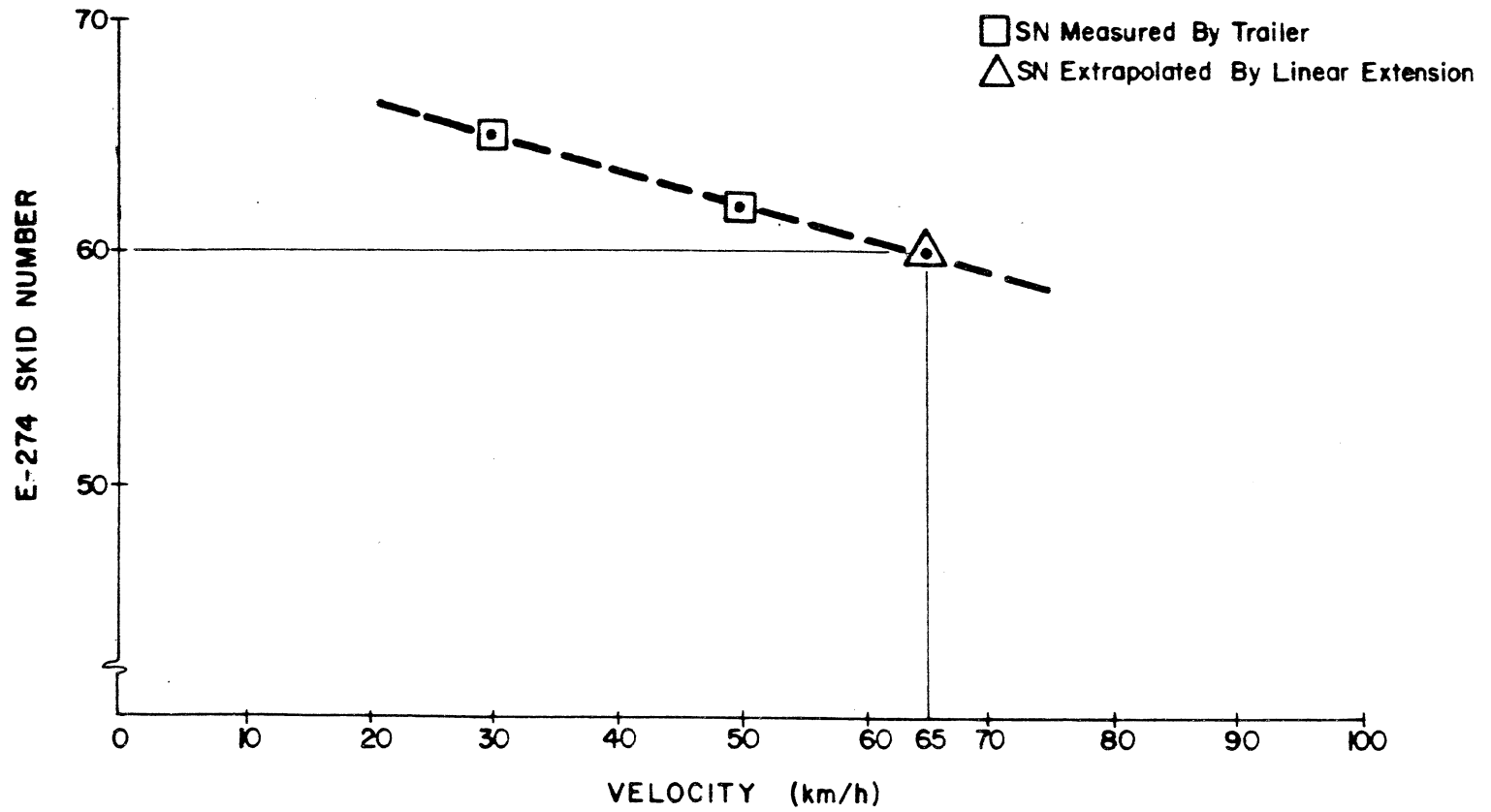


Figure 11. Extrapolation Technique for Determining SN_{65} .

Summary

The preceding pages have detailed an investigation of the capabilities and limitations of the ASTM E-274 skid trailer, especially as related to behavior in the non-tangent measurement mode. To begin with, it was necessary to develop equilibrium equations for a typical trailer in the measurement mode which were used to predict the major forces operating in the system.

Evaluations were then made by both analytical and physical measurement techniques. The results are dispersed throughout the chapter along with several techniques which it appears would extend the performance range for the trailer. Each of the proposed performance extenders are evaluated in detail later in the study. Yet the most significant result of this study, at least through the end of this task, is that even though the E-274 type trailer possesses the limitations outlined in this chapter, few of these limitations are within the normal range of highway design criteria. For example, in measurement up a grade, the limiting factor is the ability of the tow vehicle to maintain the proper speed while measuring. Since grades which are so steep that a speed of 65 km/h could not be maintained are extremely rare, and certainly not recommended by AASHTO, this very real limitation is not very important in the real world.

All things considered, the E-274 trailer has demonstrated that it is not only an excellent measurement technique for tangent pavement sections, but is also versatile in measuring nontangent sections. In fact, it appears to be far more versatile than most of the literature

had even remotely hoped for. Combined with the considerable capital investment in E-274 trailers and training by the various States, this investigation represents a strong statement of support for its continued use. These concepts are of course amplified in later chapters of this report.

III. ALTERNATE EQUIPMENT FOR MEASUREMENT OF SKID-RESISTANCE OF NONTANGENT SECTIONS

The literature identifies several methods for the measurement of skid resistance. The devices and techniques range from relatively simplistic approaches to complex laboratory instruments which require carefully controlled testing conditions. During the course of this study an attempt was made to investigate promising equipment that could be used for skid-resistance testing of nontangent sections, especially those which appear infeasible for the current two-wheel E-274 skid trailer.

Two major criteria were used to determine if an alternate method was worthy of detailed consideration. These criteria were

- 1) Availability of the device, and its past use for the measurement of highway skid resistance, and
- 2) Projected performance in a nontangent measurement mode.

Evaluation of the literature reviewed early in the study, led to detailed consideration of five devices other than the two-wheel E-274 type trailer. The devices considered are listed in Table 3.

The equipment considered for recommendation in the next chapter was rated in the several areas as requested by the sponsor. Each area was considered, not only regarding the equipments compliance, but also considering the relative importance or priority of that area of importance.

Preliminary Evaluation of the Candidate Techniques

Prior to full-scale evaluation, the candidate techniques identified in Table 3 were evaluated according to the scope of work as

Table 3. Alternate Devices Evaluated During Research Effort

Device	ASTM Standard	Description
Mu-Meter	E670-79	Side Force Friction - Free Rolling Wheels
Diagonal Braked Vehicle	E503-75	Automobile Stopping Distance
British Pendulum Tester	E303-78	Pendulum Impact - Lab Type
Penn. State Mark III	- - - -	Single Wheel Test Trailer
Saab Friction Tester	- - - -	Specially Equipped Automobile

identified in the prospectus of the research project:

To provide the most practical measurement technique for measuring wet-pavement friction for road segments other than tangents, the equipment or methodology developed shall meet the following criteria:

- 1. The equipment shall be an efficient measurement system for road surveys at traffic speeds.*
- 2. It shall not interfere with traffic flow or at most cause minor interference.*
- 3. It shall be rugged and require a minimum amount of maintenance.*
- 4. The initial and operating costs shall be low for use by State highway departments and similar agencies.*
- 5. The equipment shall not be complex but be readily operable by a highway technician.*
- 6. It shall be designed for wet-pavement testing, have its own wetting system, and be capable of testing under all weather conditions, except possibly below freezing temperatures.*
- 7. It shall contain an efficient data collection and processing system, relatively free from maintenance, and simple enough for operation by a technician. The data processing equipment shall be compatible with the FHWA computer equipment.*
- 8. Simple, feasible calibration procedures for the equipment shall be thoroughly documented and readily available for use.*

To facilitate evaluation of the several alternatives presented in Table 3, a comparison table was constructed. This is shown in Table 4 with the evaluation criteria listed down the right side and the items to be evaluated identified across the top. A score of ten is assigned to a technique if it exactly meets the criteria identified or if it represents the ultimate available technique. A score of one indicates that the device or technique does not meet the objectives of the criteria

Table 4. Comparison of Alternative Measurement Methods

Mu-Meter	D B V	B P T	PTI Mark III	Saab Vehicle	Current E-274	EVALUATION CRITERIA
10	4	2	10	10	10	1. Efficient for road surveys.
10	2	1	10	10	10	2. Interference with traffic flow.
5	7	9	7	7	8	3. Rugged-minimum maintenance.
4	7	9	2	4	1	4. Initial and operating costs.
6	8	10	6	5	6	5. Simplicity.
10	5	1	10	10	10	6. Wet-pavement testing and wetting system.
8	5	5	8	8	8	7. Simple, efficient data collection and processing system.
8	7	10	7	5	8	8. Simple, feasible calibration procedures.
1	3	1	4	6	5	9. Current capability for measuring nontangent sections. (w x 2)*
1	4	1	6	7	8	10. Assumed ease in adapting to extreme nontangent sections. (w x 2)*
4	9	1	8	9	8	11. Assumed correlation to vehicle behavior.
69	68	52	88	94	95	TOTALS

*Double weighted

and shows no promise of meeting these criteria in a simple or cost-effective manner. Intermediate scores indicate an attempt to rank the various approaches or to assign a performance estimate for each device.

The chart includes the E-274 trailer, evaluated in a manner similar to the other devices. The ratings identified in Table 4 were developed based on the evaluations outlined in this chapter, and the totals developed were the basis of the recommendations at the end of this and the subsequent chapter. The balance of this chapter presents evaluations of the various techniques which were used to generate the values in Table 4.

Mu Meter

The small, trailer-type unit, Figure 12, measures the side force friction coefficient generated between the test surface and the smooth tread tires on the two measuring wheels, toed-out to the line of drag. The friction value is continuously recorded for any length section desired and is reported in Mu numbers that range from 0 to 100.

The Mu Meter meets the equipment requirements outlined previously as indicated in Table 4. It is used to perform highway friction measurements by several states at this date, though it is commonly used to measure friction properties on aircraft runways.

No literature was found on the use of the Mu Meter in nontangent sections except for some precautions to be exercised during testing; i.e., "Whereas the meter can be towed safely at speeds in excess of 65 km/h (40 mph), sharp turns should always be executed at slow speed, otherwise there is a danger of overturning the meter" (5) and " Sharp

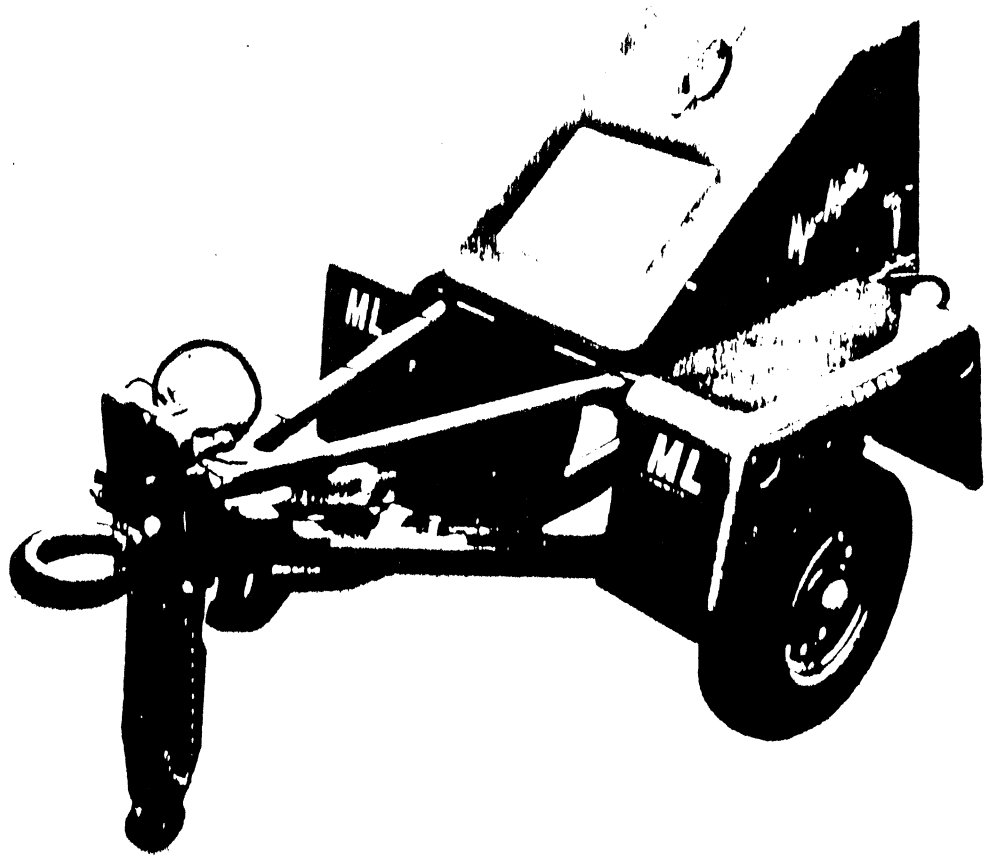


Figure 12. Mu Meter.

curves and steep grades shall not be included in a test section with level tangent sections, nor shall passing lanes be included with traffic lanes" (5).

It was felt that since the Mu Meter is in use by highway departments and had met the initial hardware requirements, a unit should be tested at the TTI Proving Grounds in a nontangent mode of operation. A used, standard M.L. Mu Meter, less recorder, was borrowed from the Air Force and reconditioned according to specifications (5). The unit was attached to the TTI Test Trailer tow vehicle using the on-board recorder and electronics for data processing. The entire system was then calibrated per specifications (11). The test plan involved the running of the Mu Meter over the asphalt test pad, Figure 13, at 65 km/h (40 mph), in a standard test configuration, in first a tangent mode then in varying levels of lateral acceleration, left and right, until an unstable condition was observed. The results of this testing are shown in Figure 14 and the ± 5 MuN points are indicated as faulty test limits (11). It is readily apparent that the Mu Meter data becomes unreliable at a relatively low lateral acceleration level. This effect is due to the nature of the unit that relies on the vertical load of both left and right toed-out wheels to be constant. Since the left wheel is attached to the pivoting frame member and the right is attached to the remainder of the unit, as shown in Figure 15, a non-symmetrical system exists. As the unit traverses a left curve the left wheel is vertically unloaded reducing the tensile force on the measuring cell. In a right curve the left wheel vertical force is increased without proportionally

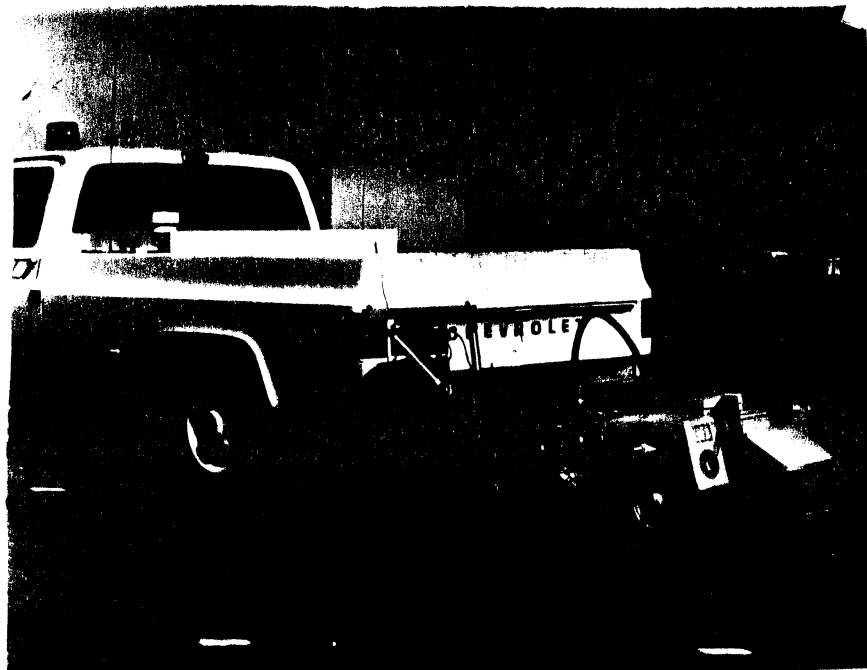
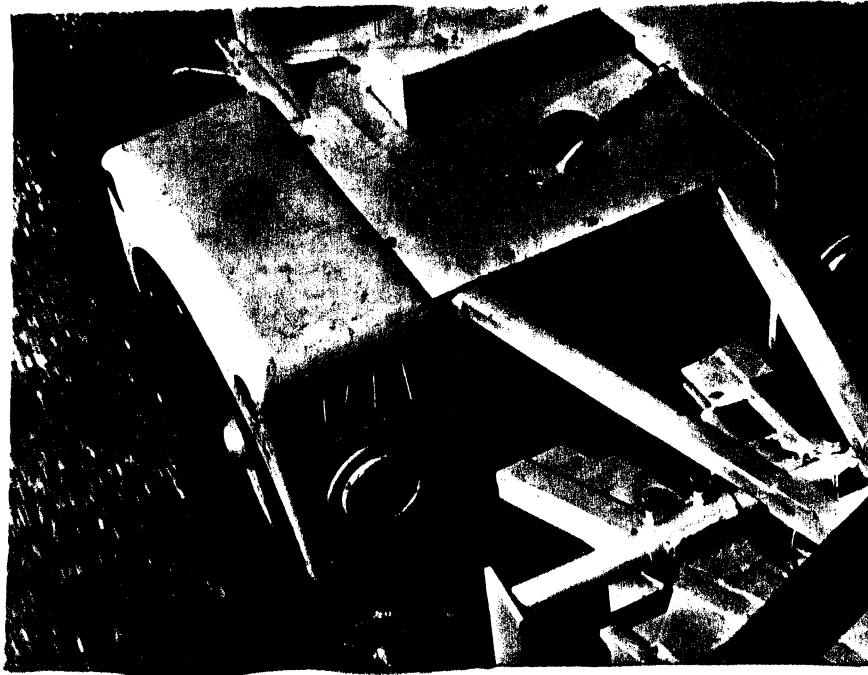


Figure 13. Mu Meter on the Asphalt Test Pad.

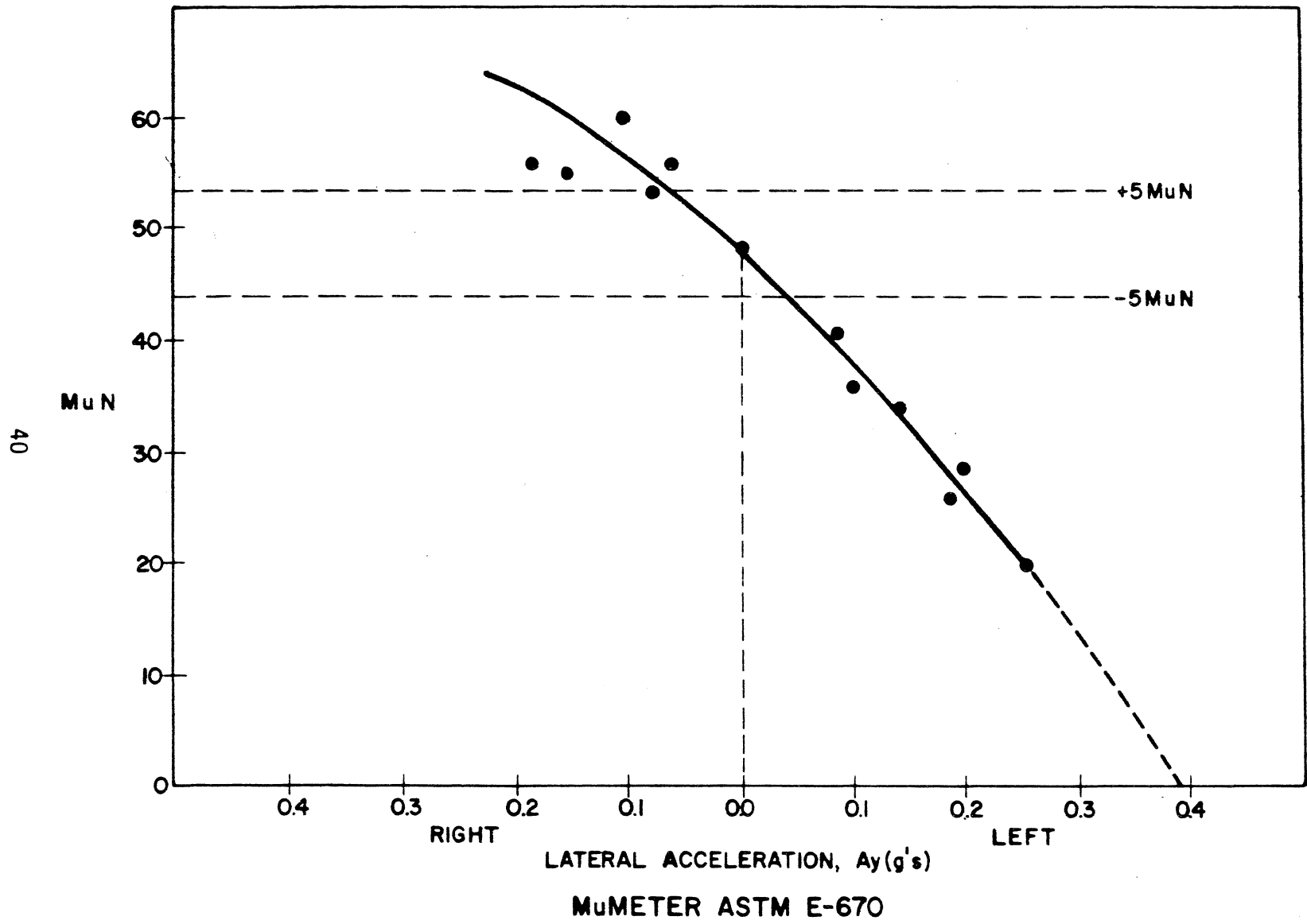


Figure 14. Results of Mu-Meter Testing Program.

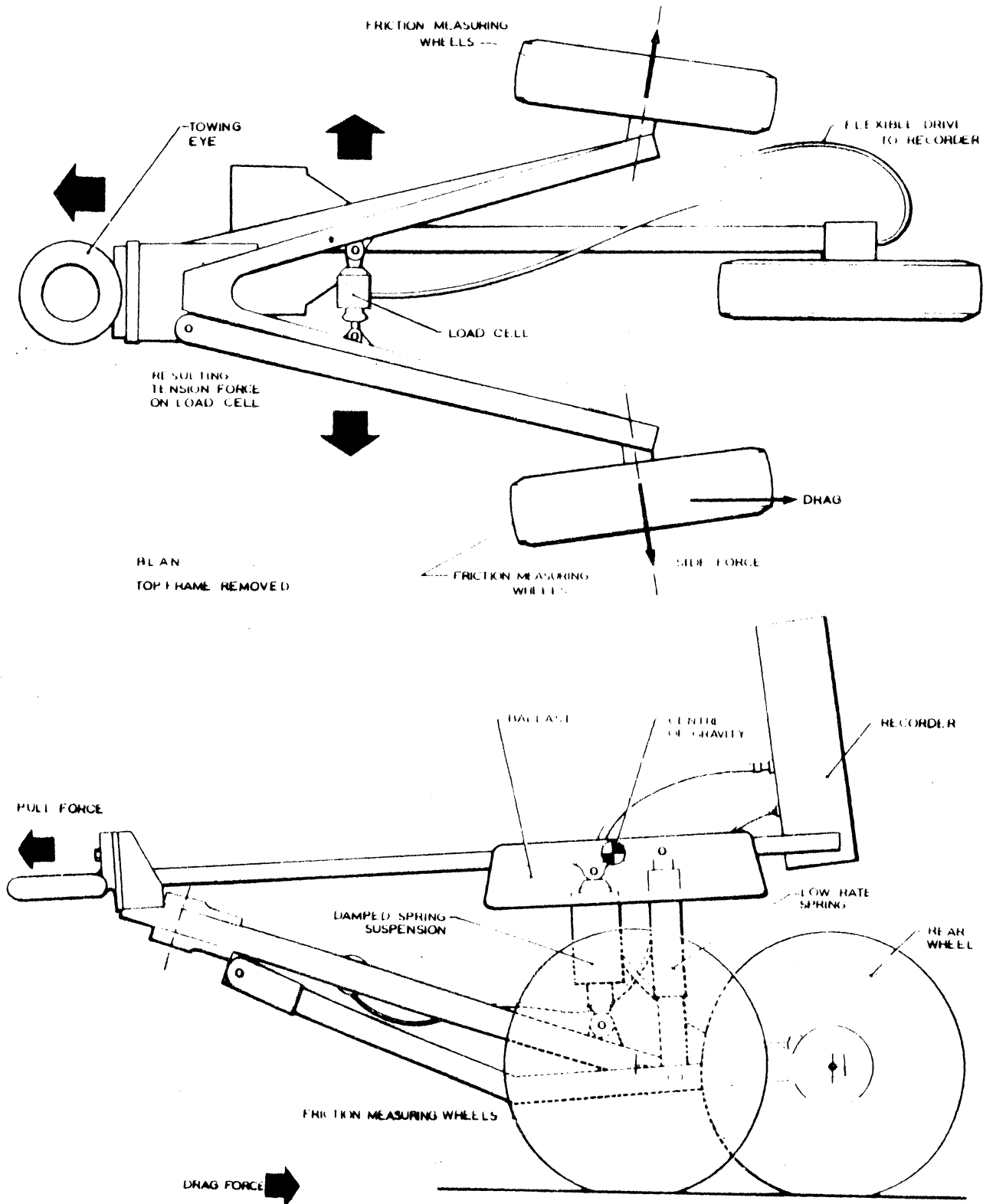


Figure 15. Diagrammatic layout of the meter

decreasing the restraining force so that the Mu numbers increase.

The track testing was terminated at a g level of 0.25 left and 0.2 right due to incipient instability of the unit. It has been calculated that the unit should overturn at a level of about 0.37 g in either direction. This level was determined by calculating the point at which the inside wheel load goes to zero using a total vertical load of 2457 N (550 lb), a wheel base of 63.5 cm (25 in), a center of gravity (c.g.) height of 53 cm (21 in), and a test wheel vertical load of 761 N (171 lb). The extended curve, Figure 14, in the left turn direction tends to verify this value while the data scatter in the right hand direction indicates a condition which is too unstable for a proper conclusion to be drawn.

Grades and superelevations were not tested with the unit due to the results of the flat curve tests. In addition, these types of nontangent surfaces produce vertical forces on the system causing significant changes in the static vertical load which is very critical to a proper Mu number measurement.

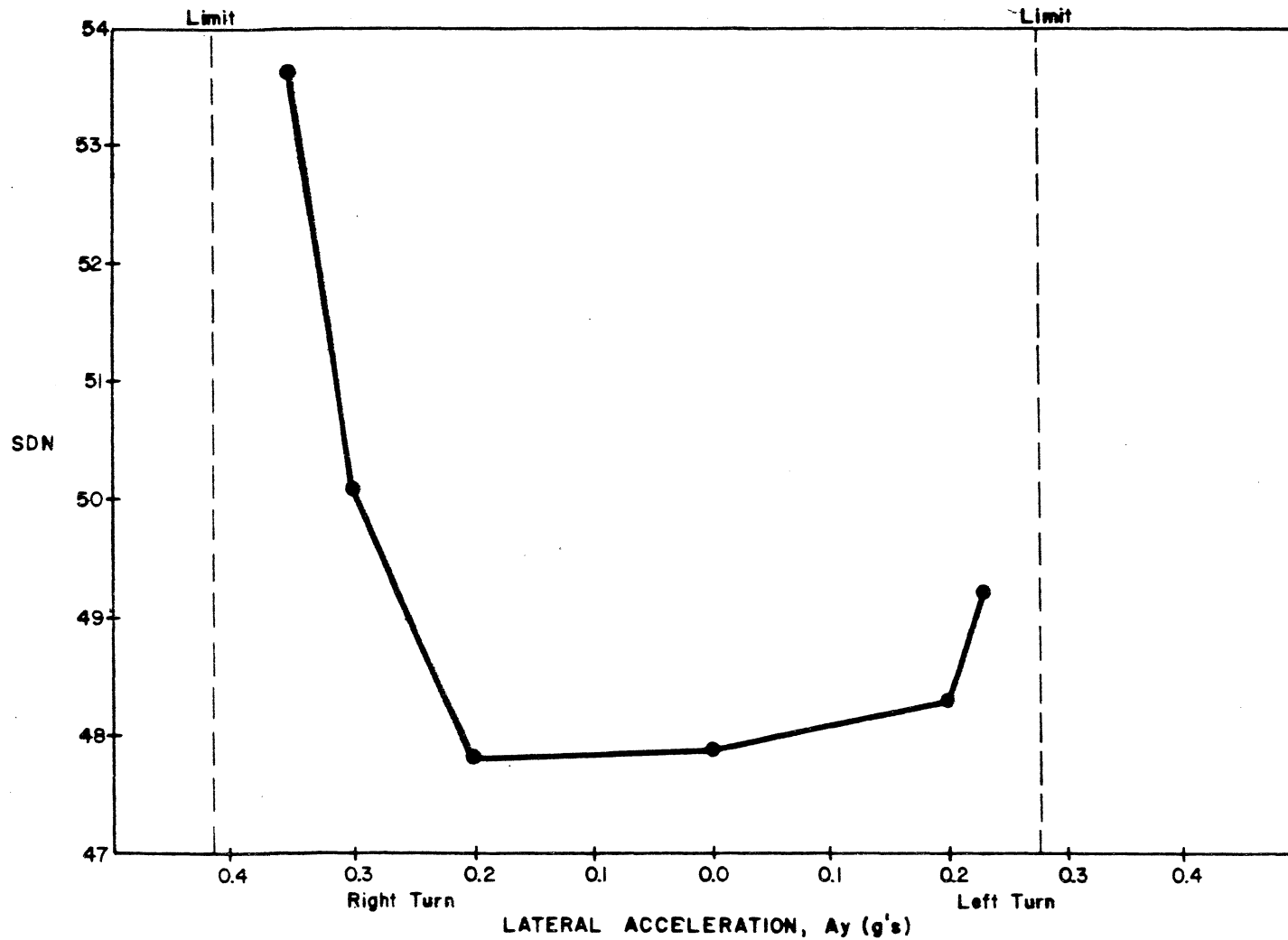
Based on these findings the Mu Meter was found to be unsuitable for nontangent measurements that produce lateral levels of acceleration greater than 0.05 g's and greater than 0.02 g's in the vertical axis. Comparison of these results to those of the previous chapter indicate that these values are well below the limits of the E-274 trailer.

Diagonal Braked Vehicle (DBV)

The test device consists of a passenger automobile with four wheels, of which a diagonal pair are braked for test purposes. The test

pavement must be wetted by another vehicle just prior to a test run. The test vehicle is then brought to speed, usually 65 km/h (40 mph), the test wheels are locked up, and the vehicle allowed to skid to a stop. A velocity deceleration increment may also be used in lieu of coming to a complete stop, however, if this technique were used a different procedure and data interpretation method from the applicable ASTM standard would have to be developed. The skid distance is measured along with the initial and, if necessary, final velocity, and a Stopping Distance Number (SDN) computed.

Referring to the equipment criteria in the scope, the DBV does not meet items 2 or 6 and could not easily be modified to do so. However, due to the simplicity of the system, and its relatively low cost, a DBV was configured and evaluated on the asphalt test pad for any insight into nontangent operation. A limited series of runs was conducted and the findings shown in Figure 16. The level of stability was first determined by conducting locked-wheel tests at increasing levels of lateral acceleration by varying the speed through a fixed radius curve. The same pair of wheels were used in both the right and left turn testing, left front and right rear. It was determined that the limit of stability, or where the vehicle could still stay within the limits of the curve, were 0.28 g for a left turn and 0.41 g for a right turn. It is presumed that a properly equipped DBV, which could brake either diagonal set of wheels, could develop the higher level in either type of turn. Data (SDN) were then taken tangent across the curve and at varying levels of lateral acceleration through the curve, in a left and right direction



DIAGONAL BRAKED VEHICLE - E503

Figure 16. Results of DBV Testing Program.

(Figure 16) up to the preestablished limits. The SDN shows good consistency up to about 0.2 g where it seems to diverge. This was apparently due to the increasing vehicle yaw, developing side force on the rolling wheels. This yaw was created by the vehicle going into an oversteer, left turn, or an understeer, right turn, condition. These conditions were observed by the driver, where he had to make steering corrections to stay within the limits of the curve, starting at 0.23 g right and 0.35 g left.

Based on these tests and published information, no practical application was found for the DBV in most nontangent measurements. However, the DBV could be used in special cases such as T-type intersections where the method of sliding to a complete stop would be a desirable measurement mode.

British Pendulum Tester

The British Pendulum Tester is a dynamic pendulum impact-type tester used to measure the energy loss when a rubber slider edge is propelled over a test surface. Being portable, the laboratory type device is capable of making various field surface friction measurements. The device is operated in a static condition, in that it does not move over the surface as a vehicle would, but is placed in position by an operator. This device was considered not as a primary measurement system, due to its obvious deficiencies relative to items 1, 2 and 6 in Table 4, but to augment the primary system by providing data where it would be difficult or impossible to operate a vehicle type measurement system.

Based on the literature review the British Pendulum Tester does not

meet the criteria items 1, 2, and 6 as shown in Table 4. It was discovered that the device must be operated on a level surface (10) which eliminated superelevations and grades, although this difficulty could probably be overcome. This would limit the normal use of the device to flat curves and low speed areas such as T-type intersections. Further investigation showed that "any correlation with Method E-274 would be purely fortuitous" (9) and "is not very satisfactory" (9).

Based on these findings it was decided not to proceed any further with investigations into the British Pendulum Tester and to consider it not generally applicable to nontangent pavement friction measurements.

PTI Mark III

The Pennsylvania Transportation Institute (PTI) Mark III Pavement Friction Tester is a modification of a single wheel tester capable of operating in the locked-wheel, transient-slip, and yaw modes. The single wheel tester uses a hydraulic cylinder to force the trailer into a yaw angle up to 12 degrees from the direction of travel. The force measurement system consists of a six-component force/moment measuring hub.

The system agrees, to a large extent, with the equipment criteria requirements outlined earlier. Item 4, in Table 4, addresses the system cost which is about \$65,000 complete, and to date the only extensive use is by the State of Pennsylvania and Penn State University. Information on this system was obtained from a Pennsylvania State University report (8) that investigates the various modes of friction testing using the PTI Mark III exclusively. It was not feasible during this phase of

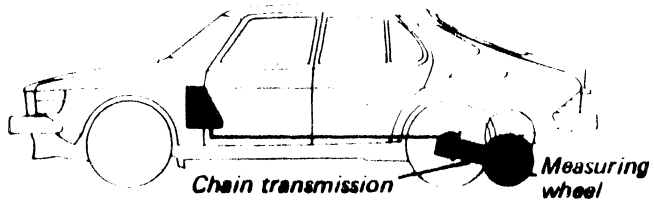
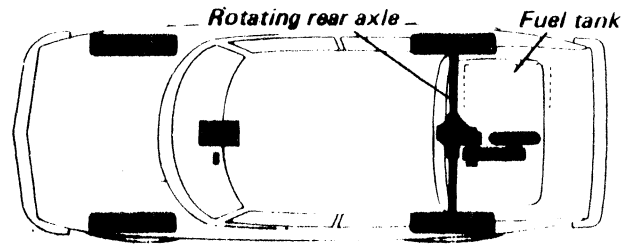
the study to obtain a unit for testing at the TTI facility due to the continuous use of the existing units and the remote distance involved.

With the system able to operate in the locked-wheel mode with an ASTM E501 (12) tire at 4826 N (1085 lb) it should emulate the ASTM E-274 two wheel system quite well. With the added capability of adjusting or locking the articulation angle between truck and trailer hydraulically, the acceptable level of lateral forces could be somewhat higher than the E-274 two wheel system. The same effect of lateral forces acting on a system with reduced side force capability exists, but the tow vehicle is used to maintain stability, not a single wheel.

Saab Friction Tester

The Saab Friction Tester is a specially equipped Saab 900 Combi Coupe' with a measuring wheel located between the rear tires, and driven from the differential at a constant 15 percent slip relative to the drive wheels. The vehicle is primarily intended for aircraft runway friction measurements according to ICAO (International Civil Aviation Organization) regulations. It is also specified as a "Road Quality Tester" in a Saab-Scania report (7) where it is "intended for periodical checking of the road surface conditions." Figure 17 shows the basic operation of the unit and the location of the test wheel. A vertical load of 982 N (220 lb) is generated by a weight via a spring and shock absorber. The test wheel can be either set to a free wheeling mode or to the 15 percent slip condition by the operator. It is conceivable that modifications could be made to provide for complete lock-up. Friction numbers, which range from 0 to 10, are recorded on a digital

A hydraulically retractable measuring wheel is built in behind the rear axle of the car.



The measuring wheel is driven by a chain transmission connected to the rear axle, and the drive ratio provides a constant 15 % slip.

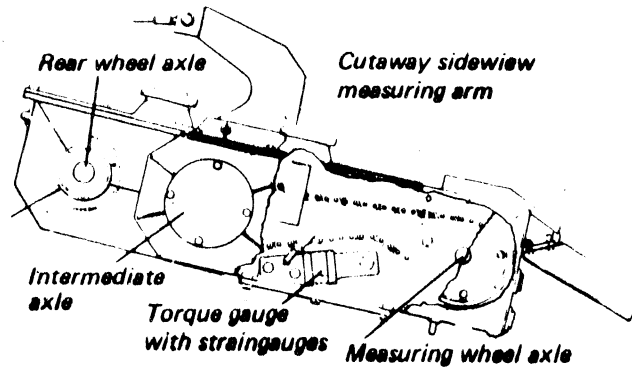


Figure 17. Saab Friction Tester.

printer and on tape recorder cassettes. The system contains an on-board watering system with a pump and 500 litre (130 gal) tank.

Since this is a relatively new device, literature and test results in relation to highway friction work in the U.S. is quite limited. A limited testing program was proposed that would involve a typical tester to be evaluated at the TTI Proving Grounds Research Center, but was disapproved by the Sponsor based on the positive testing results of the E-274 system as noted in the previous chapter.

With respect to the previously mentioned Equipment Criteria (Table 4), based on manufacturer's literature, the Saab appears to meet all points at an approximate cost of \$40,000. The unit is also claimed to measure curve radius by using a lateral accelerometer and vehicle speed to perform the calculations. This technique would work on a flat curve but would need other inputs, if any superelevation is encountered, to predict true radius.

The system appears to be capable of making measurements in a non-tangent mode of operation with no modifications since it is basically an automobile with a lightly loaded test wheel underneath. It should be able to operate at higher g level conditions than a tow vehicle -- test trailer configuration. In fact, modification of the vehicle suspension to handle curves at higher speeds would make the Saab vehicle the most promising all around skid resistance evaluation method encountered in the study.

Correlation between the Saab Friction Tester and a locked wheel trailer is not well established at this point. A study by NASA at

Wallops Island recently completed a test sequence involving the Saab system, Mu Meter, and the DBV in tangent airport runway measurements. The data from this study have not been processed at this time and no conclusions have been reached. Walter Wazinski, of the Canadian Ministry of Transportation, indicated they have a Saab system in use and have conducted a correlation study, but with a Skidometer tester which is also a slip-type tester. He indicated his is the only unit involved in highway measurements in the U.S. or Canada to his knowledge.

If future testing shows the Saab Friction Tester is correlatable with the E-274 system, it should be considered as a device to measure nontangent sections which are not feasible for the E-274 skid Trailer.

IV. EVALUATION OF ALTERNATIVES TO AND RECOMMENDATIONS FOR THE MEASUREMENT OF SKID RESISTANCE OF NONTANGENT SECTIONS

The following pages present a synopsis recommending equipment proficient for measuring the wet-pavement skid resistance of nontangent sections. The basis of these recommendations can be found in the previous chapters. The specific recommendations presented are based on evaluation of the information summarized in Table 4 and on consideration of the factors discussed below.

Use of Existing Equipment

This criterion ranks quite high in the selection of a practical system for friction measurements of nontangent sections. If an existing system can be used as it is or with slight modification, the modification cost factor will be minimal. Also, the systems would be available with relatively large amounts of background data. Since prior analysis indicated the relative capability of existing measurement systems to perform nontangent measurements, it is recommended that they be considered for use or further development in measuring skid resistance of nontangent sections. These systems, listed below, are ranked in order of existing number of units used for highway testing.

- 1) Two-wheel E-274 type trailer.
- 2) Mu Meter.
- 3) PTI, single wheel trailer.
- 4) Diagonal-braked vehicle.
- 5) Saab Frictional Tester.

Modification of Existing Equipment

Recommended modifications to existing equipment were treated with respect to cost and equipment inoperative time involved versus the benefits gained. The results presented earlier showed that a, properly configured, two wheel E-274 skid trailer could satisfactorily conduct nontangent testing within certain limits. These limits, as described, occur mainly as an instability in the trailer as lateral acceleration increases producing a hazardous condition at approximately ± 0.33 g. If the system is to be used as it is, it is recommended that an audible-visual warning system be developed to alert the operator of a hazardous condition, if the limit is exceeded. If measurements are planned to be made above this limit, it is recommended that a method or methods of stabilizing the trailer unit be developed as outlined earlier (e.g., a trailing wheel), or that different measurement procedures be adopted.

If E-274 systems that do not measure the dynamic test wheel vertical load are to be used in nontangent measurements, it is strongly recommended that a system be developed to conduct this measurement as described earlier. Such a system is developed in the next chapter. Other modifications recommended for the E-274 system would be to provide baffles in the water tank and modify the water nozzles to distribute the water in front of the test wheel even for sharp curves.

The Penn State (PTI) Mark III single wheel tester, of which there are only six in use, conforming to ASTM E-274 should require only one major modification. The articulation angle for the yawed wheel should be held fixed during a test. It is recommended this be accomplished by

modifying the hydraulic controls associated with the yaw system. This system could have a higher lateral acceleration limit than the two wheel E-274. However, substantial testing of the device as modified would be required to establish its true behavior pattern since the stability of such an arrangement is still questionable.

The Diagonal Braked Vehicle, as stated in the last chapter should be limited to the testing of flat road surfaces at low speeds where a full stop is normal for traffic operation. T-type intersections are applicable examples. Recommended modifications for the DBV would be to add an on-board watering system to eliminate the need for a separate water truck. An accelerometer should be installed for instantaneous display of rate of change of vehicle velocity throughout the test.

Due to the sparsity of test data available on the Saab Friction Tester, no modifications are recommended to improve its nontangent performance at this time.

Changes in Testing Procedures

The most economical and expedient method of adapting existing equipment to measure nontangent sections would be to develop operating procedures to maximize the strong points and minimize the weak points. The following outlines several possibilities for such procedural changes.

Test velocity is a major concern since the centrifugal force acting on the system is increased as the square of the forward velocity. It is recommended that a method be devised to test at reduced speeds for high lateral g test sites, and to interpret the results for data to the accepted 65 km/h (40 mph) test speed. Another recommended procedural

change would be to require a broader range of calibration levels for the test wheel vertical load data system. This is to accommodate the higher dynamic range required during nontangent testing.

The same recommendations hold true for the one wheel test trailers, in that, the same type of forces would affect it and could be substantially reduced by a reduction in test speed. As mentioned in the equipment modifications a procedure should be developed to fix the articulation angle between tow vehicle and test unit. This should provide reasonable stability in a repeatable manner; however, it should again be emphasized that this would be a procedure requiring substantial validation, due to the uncertain stability of this configuration.

The Diagonal Braked Vehicle used at T-type intersections would require the development of special procedures for measuring the deceleration or stopping distance. It is recommended that a pulsed method be developed using the afore mentioned accelerometer, similar to the DBV system used by NASA at Wallops Island.

Inadequate information is available to recommend any procedural changes for the operation of the Saab Friction Tester.

Conceptual Design of New Equipment

No original design of equipment is recommended for the measurement of nontangent, wet-pavement skid resistance at this time. This recommendation is based on the findings of the previous chapters regarding the capability of existing systems.

Adequacy for Measuring Tangent Sections as Well as Nontangent Sections

The equipment recommended for measurements of nontangent sections is basically existing tangent type equipment with some hardware and procedural modifications. The proposed modifications are intended to augment the already existing capability and accuracy of the system without degrading its designed capabilities in the tangent mode of operation.

Summary

Based on these results, it is recommended that the two wheel, E-274 Skid Trailer be used, with proposed modifications, as the primary method of measuring the wet-pavement skid resistance on nontangent sections.

The proposed modifications include the following:

- 1) Incorporation of an audible-visual warning system to alert the operator(s) of a hazardous condition (developed in the next chapter).
- 2) Incorporation of an "effective dynamic force system" for trailers which do not now measure these forces directly, as outlined in the Task B report (developed in the next chapter).
- 3) Provide baffles and reconfiguration of the water-distribution system to prevent catastrophic loss of water during testing.
- 4) Develop procedural changes for extreme nontangent operation as follows (developed in the next chapter).
 - a) A sequence of "safe" or "posted" speed operations which allow extrapolation of an SN_{65} .
 - b) Posted speed operation which develops and reports skid-resistance values at arbitrary (posted) speeds.
 - c) Posted speed operation combined with some other type of testing which would allow analytical determination of the SN_{65} , as described in Chapter II.

At this time, it does not seem necessary to recommend use of the other promising methods for nontangent measurement described herein. The lack of experience with these devices (the PTI one-wheel tester and the Saab vehicle), their high initial cost, and the prevalence of the two-wheel E-274 trailer and the lack of promise that either of the alternate approaches could offer better performance, supports these recommendations.

V. TECHNIQUES USING THE TWO-WHEEL ASTM E-274 SKID TRAILER FOR THE WET-PAVEMENT MEASUREMENT OF SKID RESISTANCE OF NONTANGENT SECTIONS WITH ADDITIONAL INSTRUMENTATION FOR DYNAMICALLY MEASURING HIGH-WAY GEOMETRICS

With the E-274 Skid Trailer showing the most promise, the following pages will document details of the recommendations presented at the end of the last chapter. As the E-274 Skid Trailer is already a widely used, well documented, and readily available piece of test equipment, the task of equipment design is greatly simplified. Even though the performance of the standard E-274 system in nontangent measurement is good, two areas require attention. The first is the upper limit of the system. This is the point which, if exceeded, produces not only erroneous results, but a condition that is unsafe to the system operators and any vehicle or persons close to the system. This limit is one of stability of either the tow vehicle or the trailer. As the severity of curvature, slope or geometric condition increases, the measurement system becomes victim to the very situation it is trying to measure. Test track testing, earlier reported, showed that the trailer is the first part of the system to become unstable. These tests showed that as the radius of curvature becomes smaller and smaller, and the speed is maintained at 65 km/h (40 mph) the trailer starts to yaw or slide-out due to the greatly reduced side-force capability of the locked wheel. This event does not happen gradually with warning, but quite rapidly as the test wheel is locked to take a measurement. This phenomenon was discussed in earlier chapters. Since the track testing was terminated at incipient slip-out conditions to prevent damage,

jackknifing or complete slip-out did not occur, but could be anticipated. The level of incipient slip out is rather high compared to normal highway travel (approximately 0.3g to 0.4g in the trailer's horizontal plane). This level also approaches the stability limit of the tow vehicle.

To increase the upper limit of side force allowable on the test trailer, the cornering slip resistance of the system must be increased to meet the increased demand. Based on the findings presented earlier, the standard E-274 system, in a locked-wheel test mode, relies on the rolling wheel to generate effectively all of the required side force. The side force available could be simply expressed as:

$$(7) \quad F_{ya} = C_{\mu} W_r$$

in which

F_{ya} = Available side force.

C_{μ} = Cornering slip number/100, dry.

W_r = Static weight supported by the rolling wheel.

In order to maintain a stable system, this available side force must never be exceeded by the side force demand produced by lateral acceleration caused by cornering or geometrics. This demand is simply expressed as:

$$(8) \quad F_{yd} = W_t A_y$$

in which

F_{yd} = Side force demand.

W_t = Static weight supported by both wheels.

A_y = Lateral acceleration.

There are two other significant forces which affect the limit of stability. The first of these is the side force produced as the test wheel is locked, applying a moment about the hitch point. The contribution of this force in a right turn with the left wheel locked is

$$(9) \quad F_{yd} = (W_t A_y) - F_s$$

in which

F_s = Side force developed due to locked wheel.

It should be noted that this force is dependent on SN.

The other significant force is the overturning moment which increases or decreases the vertical force of the wheels as the lateral acceleration acts on the center of gravity of the trailer. This effect adds or subtracts from the available side force.

$$(10) \quad F_{ya} = C (W_r - W_t A_y h/t)$$

in which

h = Height of c.g. from ground, and

t = Wheel track.

It is interesting to note that the side force F_s counter balances the effect of the load variations of the rolling wheel, to some extent, providing a directionally symmetrical system. Typical available and demand side forces are shown in Figure 10 at various lateral accelerations conditions.

The lateral accelerations (A_y) are measured in a plane parallel to the trailers axle in the Y axis and are independent of vertical grade and cross slope. Since the lateral acceleration measured by an accelerometer firmly mounted to the trailer axle is a direct indicator of

stability level a warning system can be devised from its output.

By applying the output voltage from such an accelerometer to an electronic voltage comparator along with a preset level, a warning signal can be generated. This signal, whether in the form of a bell or light would indicate to the vehicle operator that the skid trailer could go into an unstable condition if a locked-wheel test is performed during that particular maneuver. The particular section of roadway could then be rerun at a lower velocity to reduce the dynamic forces on the test trailer. A further step in providing a safe system would be to couple the output of the comparator to the skid-cycle controller as an inhibit signal to prevent a test-wheel lockup in the event of an unsafe condition. A block diagram of such a system is shown in Figure 18.

The upper limit of stability of the test trailer may be increased allowing measurements to be made in geometric roadway conditions producing high lateral forces. One method of accomplishing this is by increasing the vertical force on the rolling wheel allowing a higher cornering force as expressed in Equation 7. To produce this increased force, weights could be added to the right side of the trailer (assuming a left test wheel). Since the weights could not realistically be placed directly over the wheel, some weight would need to be removed from the left side to maintain test weight. The available side-force capability would be expressed as:

$$(11) F_{ya}'' = C\mu (W_r + W_a - W_t A_y h/t)$$

in which:

W_a = Additional load applied to rolling wheel

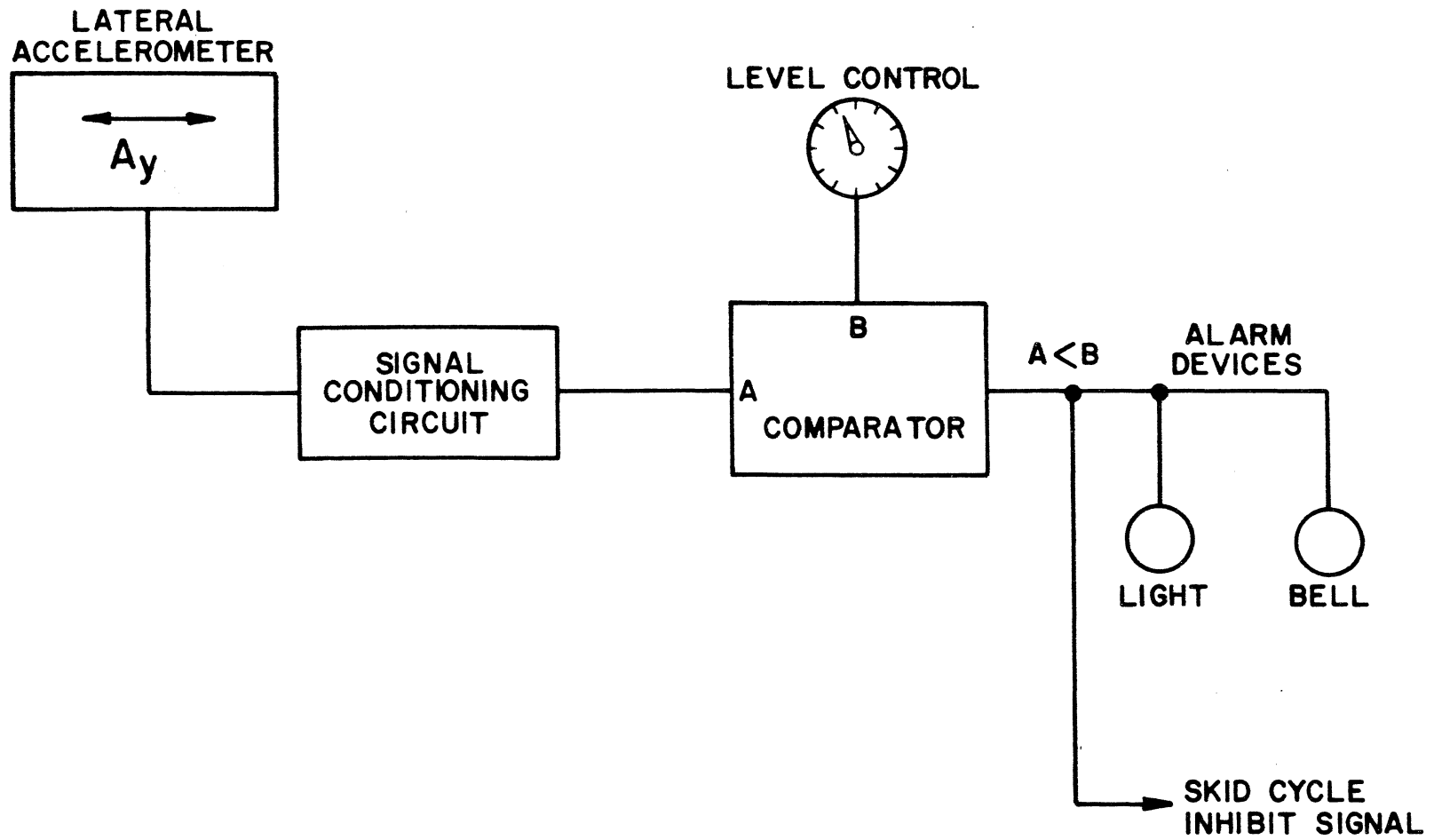


Figure 18. Block Schematic of Operator Warning Device .

As W_t is still the total static weight supported by the wheels it must also increase as the rolling wheel is loaded. This increased weight or mass is acted upon by lateral accelerations and also causes an increase in side-force demand as shown in Equation 9. Fortunately F_{ya}'' increases at a higher rate than F_{yd} as the load increases, producing a beneficial condition. Figure 19 illustrates the net effect of adding weight to the rolling wheel and maintaining the test wheel static weight. Maximum allowable A_y is the point at which the trailer could go unstable and spinout on a dry roadway, and is found by:

$$(12) \quad A_{y \max} = \left[F_s + \mu (W_r + W_a) \right] / \left[W (1 + \mu h/t) \right]$$

The dotted line shows the effect of the reduced side force component F_s caused by a lower wet friction surface.

Since placing weight directly over the free wheel is not practical, another approach could be the addition of a third wheel to the trailer. This wheel would be supported from the rear of the trailer by means of a vertically hinged joint. This third wheel could then be loaded with dead weight to produce additional side force capability. The same formula (6) applies to the three wheel condition as to the two wheel trailer with the exception of the effects of different moment arm length and c.g. location.

Another approach to the small radius measurement problem would be to operate the E-274 system at a reduced test speed. Rather than conducting all tests at the normal speed of 65 km/h (40 mph) the surface could be measured at traffic or posted speeds. This would allow a much smaller radius to be measured since the side force is a function of the

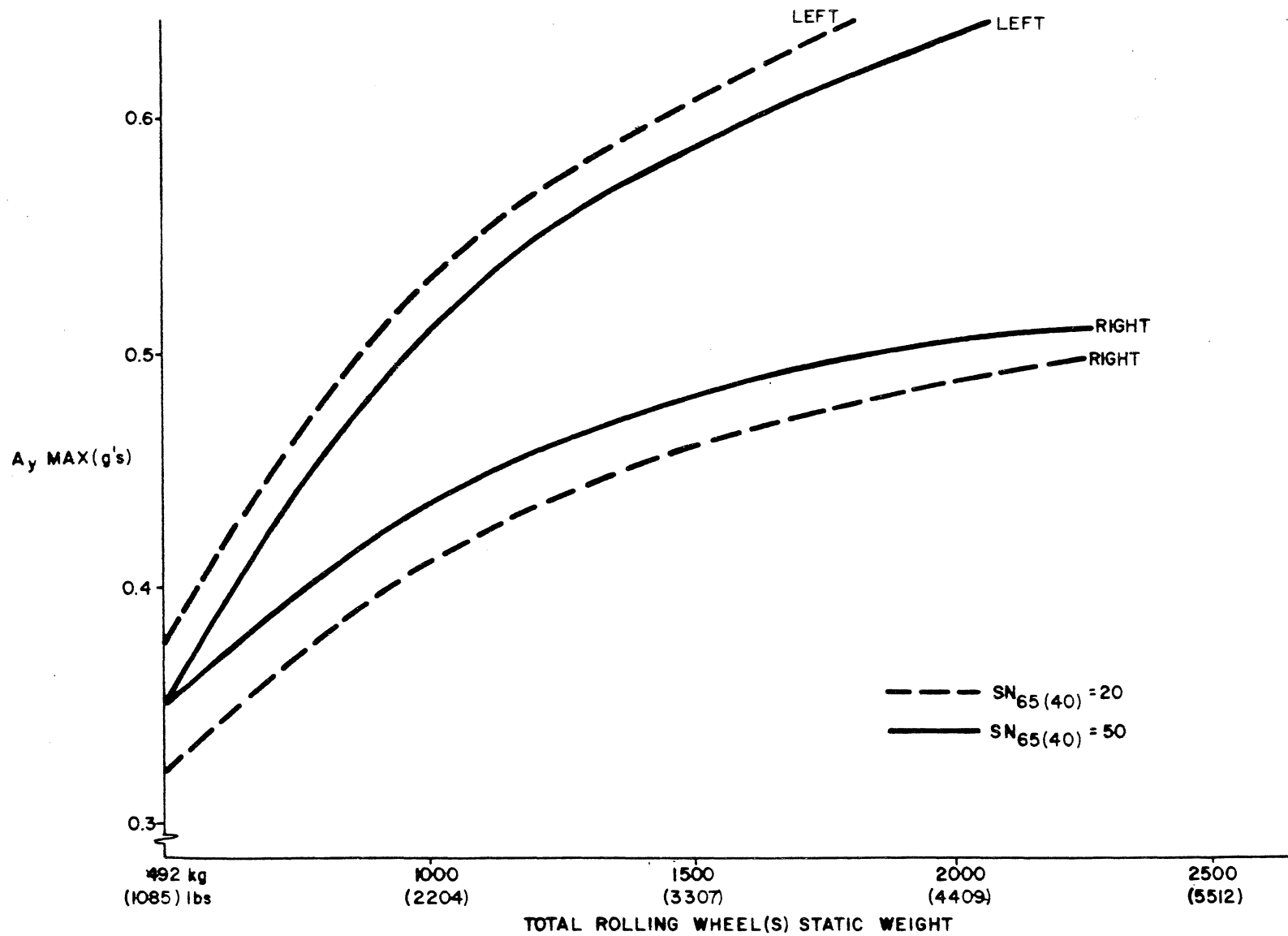


Figure 19. Effect of Adding Weight to Unlocked Wheel.

square of the speed. To correct the data back to the standard SN_{65} (40) framework, i.e., to correlate with tangent measurements, a speed gradient would have to be established for each range of Skid Numbers. An alternative to the gradient approach would be to use a technique similar to the one outlined in Chapter II on pages 28 through 29. Evaluation of these alternatives will be considered during Phase II of the project.

The other required refinement to the E-274 system is the correction of data at marginal conditions. This correction would be performed by electronic function modules placed in the data processing system. These modules would produce a voltage proportional to either the angular misalignment of the measurement axis to the true forward axis or the side force applied to the measuring wheel, or both. This error signal will then be summed with the data to produce a value as though there was no error. As the errors have been found to be small, based on test track work, a fairly simple circuit should suffice correcting for the major of the several error producing factors. Several circuits have been discussed and will be evaluated in Phase II.

For those E-274 systems which do not presently measure horizontal and vertical forces directly at the locked wheel, a technique has been developed to correct the data output. This technique involves using accelerometer signals to "correct" the static wheel weight for the errors induced by nontangent measurement. A block schematic of a circuit which can accomplish this correction is shown in Figure 20. The basic purpose of the circuit, is to correct the static wheel weight for the dynamic vertical and lateral accelerations of the trailer, and to use this

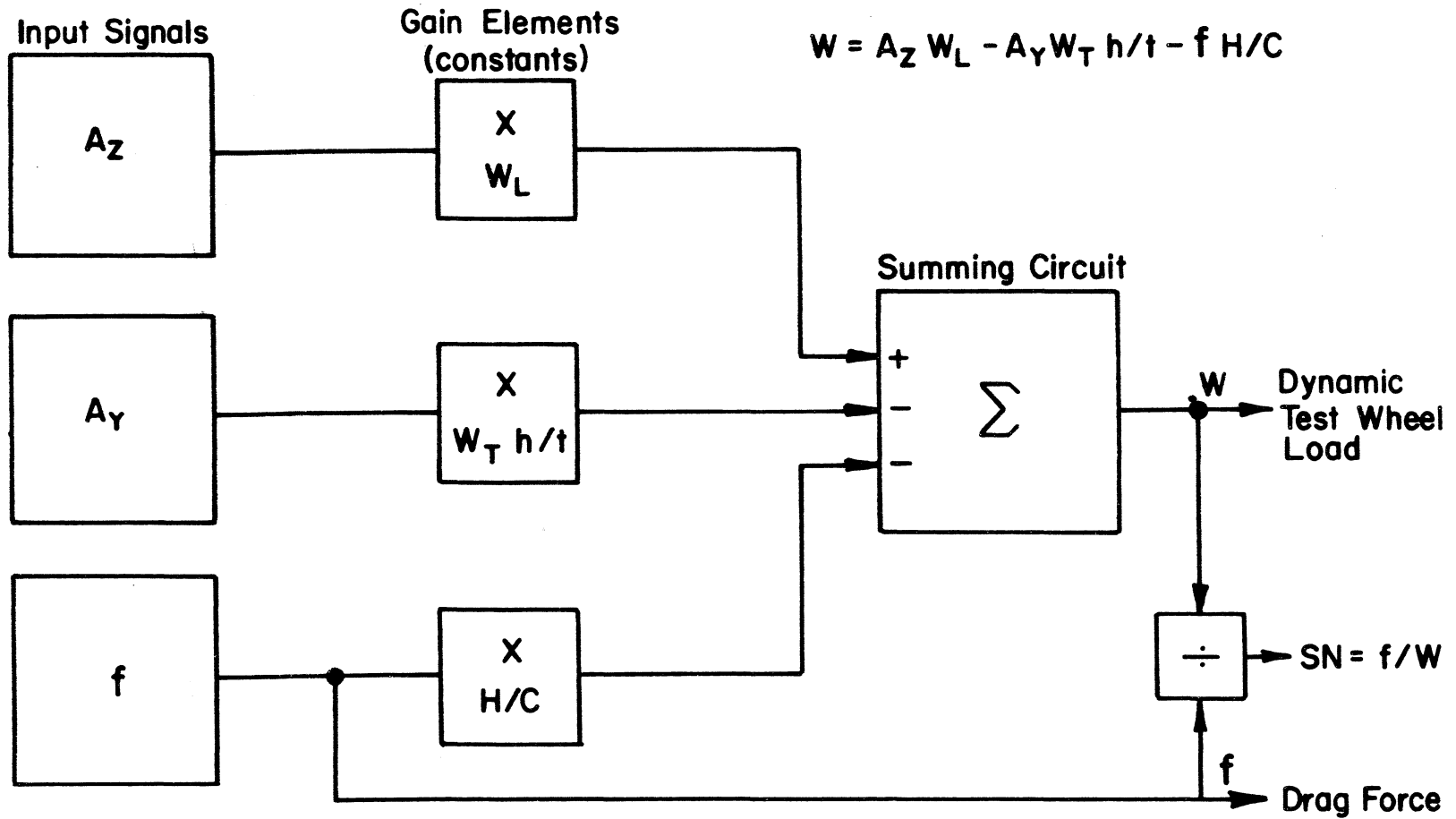


Figure 20. Block Schematic of Correction Circuit.

corrected value to find the skid number. The equations used are as follows:

$$(13) \quad SN = (f/w)(100)$$

Where:

SN = Skid number at test speed

f = Draw bar force, N (lbf)

$$W = A_z W_1 - A_y W_t \frac{h}{t} - F \frac{H}{c}$$

and

W = Dynamic test wheel vertical load, N (lbf)

W₁ = Static test wheel vertical load, N (lbf)

W_t = Static test trailer weight, N (lbf)

A_z = Vertical acceleration at c.g. of trailer (g)

A_y = Lateral acceleration at c.g. of trailer (g)

h = Height of c.g. from level ground, m (ft)

t = Wheel track of trailer, m (ft)

H = Height of hitch center from level ground, m (ft)

c = Distance from hitch center to axle center, m (ft)

To provide direct, dynamic measurements of the roadway geometry a system separate from the acceleration measuring system has been developed. This system will involve a gyroscopic system similar to those used in aircraft and aerospace work. The gyro is a device using angular momentum of a spinning rotor to sense angular motion of its case with respect to inertial space about one or two axes orthogonal to the spin axis. A vertical gyro will measure angular changes in both the pitch and roll planes while a directional gyro will measure angular changes

in the yaw plane. Systems are commercially available that utilize aircraft type gyros for land vehicle research. These units provide a voltage output directly proportional to any angular displacement from true horizontal.

The earth's horizontal plane is sensed by mercury gravity switches located on the gyro mechanism. These switches drive low torque motors to position the gyro mechanism to a perfectly vertical orientation. Based on past experience with this type of aircraft gyro in land vehicle work, some modifications need to be made to the commercial units for satisfactory operation. Of the several modifications and refinements required, the most obvious are the effect of acceleration on the mercury switches and the angular difference between the trailer frame and the roadway. With respect to the switches, any lateral or longitudinal acceleration will act on the mercury causing the gyro to sense an error in horizontal alignment and start torquing away from true horizontal. TTI engineers have solved these problems on a similar system for the Texas State Department of Highways and Public Transportation, and will utilize similar solution techniques on the specific instrumentation used in the Phase II effort.

VI. VEHICLE HANDLING TESTS WHICH SHOULD RELATE SKID EQUIPMENT TEST RESULTS TO PASSENGER CAR PERFORMANCE

The fundamental requirement of a routine pavement friction tester is to provide meaningful measurements related to frictional needs of traffic. These frictional needs are quite complex being a combination of skid resistance, where the tire slides, and slip resistance, in which the sliding speeds experienced by the tire tread are small in relation to the vehicle speed. There are then three modes of slip; brake, drive, and cornering.

Each mode of friction resistance measurement requires a separate test procedure and usually a different test device. The E-274 skid trailer was designed and specified to measure surface friction in the skid or locked-wheel mode of operation. Even though this mode of measurement does not reflect all the frictional needs of day to day traffic flow, it is an efficient tool for identifying skid-prone sections of roadway.

The multitude of tire-road system variables affecting vehicle skid performance makes an absolute measurement of skid resistance very difficult. As vehicle variables such as speed, load, and suspension characteristics are added, reliable measurements become virtually impossible. For this reason, vehicle handling tests cannot concentrate on developing comparisons based on absolute numbers, but on evaluating the ability of the measurement system to rank surfaces in the same order as an average vehicle.

The current two-wheel E-274 systems have demonstrated an ability to adequately perform this ranking when making tangent measurements. It therefore seems reasonable to assume that this ability will carry over into nontangent measurements. However, the influence of combined mode operation (braking and cornering, for example) may introduce subtle variations.

Recommended Procedures

Correlation of nontangent trailer performance would logically be best with a vehicle operating in a similar, nontangent mode. This implies that the developed vehicle handling test procedures should subject the vehicle to the same or similar maneuvers that the measuring trailer will experience. From our previous discussions, this would include only legitimate highway design concepts plus a few thousand situations which might not be considered legitimate. This presents us with a plethora of possibilities, the complete evaluation of which would be impossible.

Our task then is to choose a series of representative maneuvers which should cover the gamut of possible situations or represent the reasonable extremes of vehicle-trailer operation. It would also be useful if the procedures chosen correspond to some standardized vehicle handling test procedures so that the techniques and terminology used as well as the output parameters, can be uniformly implemented and interpreted.

The Vehicle Handling sub-committee of the Passenger Car activity within the Society of Automotive Engineers (SAE), has been dealing with the development of such procedures for several years. To the present

date, little has been accomplished toward establishing the unified standard. Major disagreements still exist concerning which maneuvers to use, and whether the tests should be open-loop (with an automatic controller) or closed-loop (with a human driver). It appears that it will be some time before a consensus decision will be reached.

Other avenues for developing such procedures have been more fruitful in producing techniques, but no more successful in obtaining agreement on the proposed procedures. Certainly the most successful were developed by the Highway Safety Research Institute and the Texas Transportation Institute under joint contract with the Department of Transportation (3). These procedures offer the flexibility of either open or closed-loop control while identifying limit performance characteristics of the vehicle-tire-pavement combination under evaluation.

Evaluation of the various procedures in the above referenced report, identified four techniques which show promise of correlation with the E-274 type trailer. The procedures identified are listed below.

- 1) Straight-line braking
- 2) Lateral acceleration in a turn
- 3) Braking in a turn
- 4) Acceleration in a turn

The first task, straight-line braking, relates to the normal tangent operation of the trailer. Any evaluation should include this maneuver to establish the validity and tracability of the tangent performance of the measurement technique. The mechanism of evaluation is the time increment of a velocity change under locked-wheel braking. Two

approaches to this mechanism will be evaluated during the Phase II effort; a velocity change from 65 km/h (40 mph) to 0 km/h, and a change from 75 km/h to 55km/h. The evaluations of Phase II should identify which of these approaches is most consistent and representative.

The second item, lateral acceleration in a turn, establishes the unbraked cornering capability ranking of the pavement. Again, two approaches may be used; establishing the minimum curvature negotiable at 65 km/h and the corresponding lateral acceleration, or establishing the maximum negotiable speed (and lateral acceleration) for a given curve.

Braking in a turn, item three, is a repeat of item two, except that a certain braking pressure is applied. The level of braking is usually in the neighborhood of fifty percent slip, the proper pressure being established through preliminary testing.

Item four, acceleration in a turn, is not strictly a procedure developed in the referenced report. This procedure should be performed and evaluated in precisely the same manner as items two and three, except that the curve should be entered at 55 km/h and the vehicle accelerated to 75 km/h for a given curve, with the lateral acceleration as the test output.

As stated earlier in this chapter, these procedures should be used to rank the various pavement-geometry configurations. This ranking should then be compared to the ranking by the E-274 trailer to establish the correlation.

VII. RECOMMENDATIONS FOR THE PHASE II PROJECT WORK PLAN

The introduction has already identified the purpose of the Phase II effort as the implementation, validation, and refinement of the recommendations presented earlier in this report. It is proposed that this purpose be accomplished by making use of the nine tasks as outlined in the original prospectus and proposal, with few substantive changes.

Upon approval of the recommendations presented earlier, and on notification to proceed, purchase orders for the major items required to complete tasks A, B, and C will be prepared, and copies submitted to the contract manager for final approval. Items which are supportive in nature, or which cost less than fifty dollars, will not normally be submitted to the contract manager. Procurement procedures for one item required for Task A, the tri-axial wheel force transducer, have already been instituted on contract manager approval. Delivery of this major item is anticipated in early February of 1980. The balance of equipment required for the completion of tasks A, B, and C will be ordered early and timed for receipt so that the entire modified E-274 trailer will be completed, checked-out, and ready for calibration within one year of notification to proceed, as shown in Table 5.

The unique features of the trailer to be developed in Phase II are listed below:

- 1) Incorporate warning device for incipient trailer slip-out,
- 2) Install a two-axis load cell on the measuring wheel and a tri-axial load cell on the other,
- 3) Incorporate the "effective dynamic force system" so that side-by-side measurements can be made on the two alternative measuring systems,

Months after approval to proceed

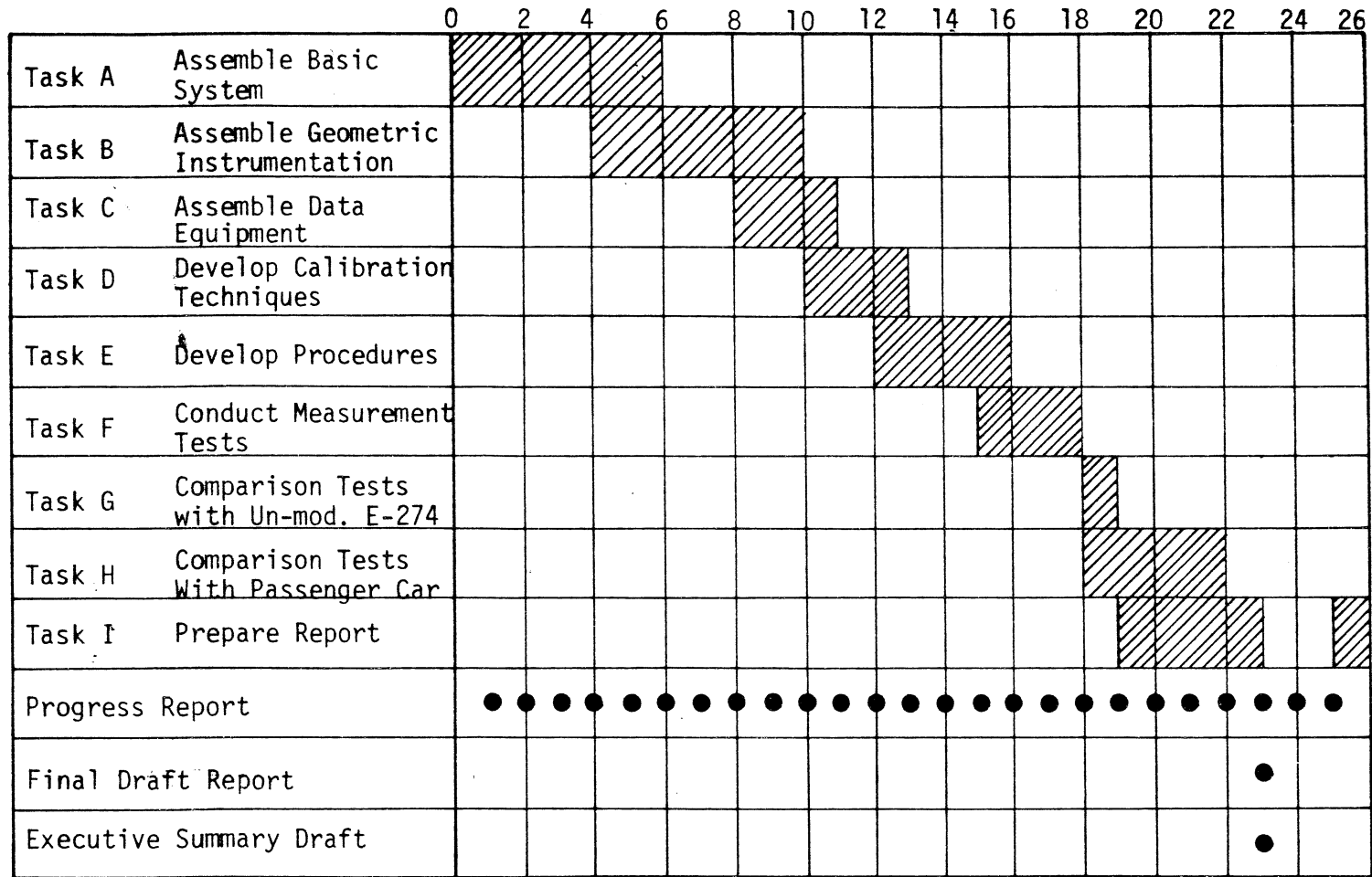


Table 5. Project Schedule (Phase II)

- 4) Provide baffles and reconfiguration of the water-distribution system,
- 5) Incorporate instrumentation for the dynamic measurement of highway geometrics, and
- 6) Possess separate data handling systems for the two force measurement techniques and for the highway geometrics measurement.

It is proposed that these changes be made on the TTI Research Trailer which was used in the Phase I testing.

Task D will develop calibration techniques for the modified trailer. These will begin by evaluating the current calibration procedures used at the Central Western Field Test and Evaluation Center. It is not anticipated that any substantive changes will be required in these procedures, but careful attention will be paid to any deviations or difficulties encountered. Calibration techniques and a list of required equipment for calibration will also be developed at this time for those additional items installed on the modified trailer.

The efforts of Task E will concentrate on smoothing out and validating the recommended procedures of earlier chapters. It is during this effort that a final decision will be made regarding extrapolation and/or measurement techniques for those borderline sections as identified in item (4) on page 55.

Task F will involve inventory-type measurements of real world highway sections by the modified trailer which was validated in Task E. Particular attention will be paid to validation of the dynamic geometrics measurement. Correlation will also be obtained between the nontangent sections measured and similar (same material, same construction time and

traffic) tangent sections as measured by the modified trailer.

Task G will be used to compare the modified trailer with the behavior of an unmodified E-274 trailer. If TTI is in possession of ARSMS #2 when Tasks F and G are conducted, this correlation will involve real-world highway measurements of tangent sections. In any event, the testing will also involve a full correlation with ARSMS #1 at the CWFTC in a manner identical to that used for calibration of systems brought to the Center. The purpose of these tests will be to establish the deterioration, if any, of the tangent performance of the modified trailer.

Task H will establish the ranking ability of the procedures developed in the previous chapter. This evaluation will involve testing on real-world highway sections and at the Research Center. Comparisons will then be made on the ranking ability of the modified trailer and the vehicle handling test procedures.

The final report, to be developed in Task I, will document the test results and present finalized, validated calibration and testing procedures.

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10. "Standard Test Method for Measuring Pavement Surface Frictional Properties Using the British Portable Tester", ASTM E-303.
11. "Standard Test Method for Side Force Friction on Paved Surfaces Using the Mu-Meter", ASTM E-670-79.
12. "Standard Tire for Pavement Skid Resistance Tests", ASTM E-501-76.

Appendix I - Computer Program Listing

```

C
C INPUT DATA SHOULD FOLLOW THE //DATA CARD. EACH INPUT CARD
C SHOULD CONTAIN 5 NUMBERS IN FREE-FORMAT:
C (1) SUPER ELEVATION (degrees),
C (2) SLOPE (degrees),
C (3) COEFFICIENT OF FRICTION (MU),
C (4) RADIUS OF CURVE (meters), AND
C (5) TRAILER SPEED (km/h).
C AS MANY CARDS AS DESIRED MAY BE INPUT.
C
BLOCK DATA
REAL VAR(6),A(6,7),BT(6),M,MU,TT(7),AVAR(6)
INTEGER*4 ILIST(6),ANS,ILEN,ILCT,ILABLE(6),KLIST
COMMON /BLK1/A,VAR,ILABLE,TT,BT,AVAR,ILIST
COMMON /BLK2/ILCT,ILEN,EXIT,I,IROT,JLIST,KLIST
DATA ILABLE / ' F ', 'Y(R)', 'Y(L)', ' S ', 'S(F)', ' R ' /
DATA ILIST/6* ' ',KLIST/' ' /
END
C *****
REAL VAR(6),A(6,7),BT(6),M,MKG,MU,TT(7),AVAR(6)
INTEGER*4 ILIST(6),ANS,ILEN,ILCT,ILABLE(6)
COMMON /BLK1/A,VAR,ILABLE,TT,BT,AVAR,ILIST
COMMON /BLK2/ILCT,ILEN,EXIT,I,IROT,JLIST,KLIST
PI=3.141592654
G=386.4
C*****VALUES FOR TTI SKID TRAILER*****
U=2340.6
H=12.5
B=12.0
T=60.63
C=111.95
E=8.8
M=W/G
MKG=M*175.08
HM=H*0.0254
BM=B*0.0254
TM=T*0.0254
CM=C*0.0254
EM=E*0.0254
WRITE(6,800)MKG,M,HM,H,BM,B,TM,T,CM,C,EM,E
IDATA=0
1 IDATA=IDATA+1
DO 890 I=1,6
VAR(I)=0.
ILIST(I)=KLIST
AVAR(I)=0.
BT(I)=0.
DO 890 J=1,7
A(I,J)=0.

```

```
ILCT=6
EXIT=0.
JLIST=0
READ(5,*,END=999)THETAD,PHID,MU,RADM,VKMH
THETA=THETAD*2*PI/360.
PHI =PHID *2*PI/360.
RAD=RADM*39.370
V=VKMH*10.936
RADFT=RAD*0.083333
VMPH=V*0.05682
GO=(M*(V**2))/RAD
```

```
C***** MATRIX FORMATION *****
```

```
A(1,1)=1
A(1,3)=-MU.
A(2,1)=H-B
A(2,2)=-E*COS(THETA)
A(2,3)=- (MU+H+E)
A(2,6)=C
A(3,2)=T*COS(THETA)+0.5+H*SIN(THETA)
A(3,3)=-T*0.5
A(3,4)=-H
A(3,5)=H-B
A(4,2)=E*SIN(THETA)
A(4,3)=MU*T*0.5
A(4,4)=-E
A(4,5)=-C
A(5,2)=-SIN(THETA)
A(5,4)=1
A(5,5)=-1
A(6,2)=COS(THETA)
A(6,3)=1
A(6,6)=1
BT(1)=M*G*COS(THETA)*SIN(PHI)+(GO*SIN(THETA)*SIN(PHI))
BT(5)=-M*G*SIN(THETA)*COS(PHI)+(GO*COS(THETA))
BT(6)=M*G*COS(THETA)*COS(PHI)+(GO*SIN(THETA)*COS(PHI))
DO 50 I=1,6
```

```
50 A(I,7)=BT(I)
```

```
ILEN=ILCT+1
```

```
CALL GAUSS
```

```
IF(EXIT.EQ.99.9)GO TO 950
```

```
C***** DATA OUTPUT *****
```

```
WRITE(6,820)IDATA,THETAD,PHID,MU,RADM,RADFT,VKMH,VMPH
```

```
DO 940 I=1,6
```

```
VARP=VAR(I)
```

```
VARN=VARP*4.448
```

```
940 WRITE(6,825)ILABLE(I),VARN,VARP
```

```
950 GOTO 1
```

```
999 WRITE(6,840)
```

```
STOP
```

```

>T5, 'M=' ,F6.1, ' kg (',F5.2, ' lb=sec**2/in) ',T42, 'N=' ,F6.4, ' m (',F5.2, ' in) ',/,
>F5.2, ' in) ',/,T5,
>'B=' ,F6.4, ' m (',F5.2, ' in) ',T42, 'T=' ,F6.4, ' m (',F5.2, ' in) ',/,
>T5,
>'C=' ,F6.4, ' m (',F6.2, ' in) ',T42, 'E=' ,F6.4, ' m (',F5.2, ' in) ',/)
820 FORMAT(///' DATA SET N',I3,/)
>T5, 'CROSS-SLOPE ANGLE (THETA)=' ,F6.2, ' degrees ',/,
>T5, 'VERTICAL SLOPE ANGLE (PHI)=' ,F6.2, ' degrees ',/,
>T5, 'COEFFICIENT OF FRICTION (MU)=' ,F6.3,/,
>T5, 'RADIUS =' ,F8.1, ' m (',F7.1, ' ft) ',
>' (+ R.H. CURVE) ',/,
>T5, 'VEHICLE VELOCITY =' ,F5.1, ' km/h (',F6.1, ' mph) ',/,
>T2, 'VARIABLE OUTPUT')
825 FORMAT(2X,A4, '=' ,F7.1, ' N (',F7.1, ' lb)')
840 FORMAT(///// 'END OF DATA',///// )
END

```

```

C***** GAUSS SUBROUTINE *****
SUBROUTINE GAUSS

```

```

C*****TRANSFER VARIABLES -A,VAR,ILCT,ILEN*****
REAL VAR(6),A(6,7),BT(6),TT(7),AVAR(6)
INTEGER*4 ILIST(6),ILABLE(6)
COMMON /BLK1/A,VAR,ILABLE,TT,BT,AVAR,ILIST
COMMON /BLK2/ILCT,ILEN,EXIT,I,IROT,JLIST,KLIST
DO 295 I=1,6
  DO 295 J=1,7
    IZOT=A(I,J)*1000
    ZOT=IZOT
    A(I,J)=ZOT/1000
295 CONTINUE
  NN=ILCT+1
  ICZOT=0
85 IROT=0
  DO 99 I=1,ILCT
    IF(A(I,I).NE.0.0)GO TO 99
    EXIT=99.9
    WRITE(6,444)((A(II, JJ),JJ=1,7),II=1,6)
444 FORMAT('0', '***** ERROR-ZERO ON DIAGONAL ****',
  > /'0',6(7(2X,E14.7))/' ')
    GO TO 999
99 CONTINUE
  DO 25 I=1,ILCT
    ZINIT=A(I,I)
    DO 10 J=1,NN
      A(I,J)=A(I,J)/ZINIT
10 CONTINUE
    IF(I.EQ.ILCT)GO TO 25
    L=I
15 L=L+1
    C=A(L,I)
    DO 20 J=I,NN
      A(L,J)=A(L,J)-C*A(I,J)

```



```
20     CONTINUE
      IF(L.LT.ILCT)GO TO 15
25     CONTINUE
      K=ILCT+1
30     K=K-1
      N=ILCT
      SUM=0.
      DO 35 J=1,N
          SUM=SUM+A(K,J)*VAR(J)
35     CONTINUE
      VAR(K)=A(K,N+1)-SUM
      IF(K.GT.1)GO TO 30
999   RETURN
      END
//$DATA
?
```