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CTS OF PAVEMENT GROOVING ON FRICTION, BRAKING, AND VEHICLE CONTROL

March 1976

Final Report

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16. Abstract

A comprehensive literature review and laboratory and full-scale tests were performed to develop mathematical models that would predict the effects of pavement grooving on friction, braking, and vehicle control. The mathematical models predict the response of automobiles, motorcycles and articulated vehicles. Based upon the test motorcycle, rider evaluation demonstrates a perceptible difference between traffic-worn and unworn grooving and the effect becomes more pronounced at higher speeds. Also, the effect of pavement grooving on motorcycle response cannot be detected from electronic instrumentation that measures steering angle and steering torque. The various grooving geometries tested do not show any significant difference for the cases considered. In addition, for a typical small car towed-vehicle combination the effects of grooving, using electronic instrumentation could not be detected at different speeds for various trailer and tongue loads. No full-scale instrumented tests were performed for an automobile. Based upon computer simulation of a medium weight vehicle, the effect of grooving is more beneficial for lower friction than high friction pavements. Also, for the case considered, a 50 mph constant steer maneuver on a 400 ft radius curve, the grooves provide a very noticeable increase in the vehicle's directional stability. Recommendations are presented based upon automobile driver and motorcycle rider evaluation of the grooved pavements, the test data, and computer simulation.

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NOMENCLATURE

a	Regression exponent of e, i.e. e^a (constant)	-
AA	Grooving approach angle; $AA \equiv X_3$	degrees
b	Regression exponent of X_1	-
$b_o, b_1, \ldots b_n,$ $b_{01}, b_{02}, \ldots b_{37}$	Constants used in generating linear combinations of the regression submodels Z_i	-
c	Regression exponent of X_2	-
C_Y	Normalized camber coefficient; $C_Y \equiv X_9$ (also called <u>cornering coefficient</u>)	lb/deg-lb [N/deg-N]
d	Regression exponent of X_3	-
e	Base of natural logarithms; $e \approx 2.71828$	-
e*	Regression exponent of X_4	-
f	Regression exponent of X_5	-
F_G	Tire force developed on a grooved roadway. Depending on context, may be either lateral or circumferential	lbs [N]
F_R	Reference (ungrooved) tire-pavement frictional force; $F_R \equiv X_{11}$	lbs [N]
FX or F_x	Circumferential friction force developed by tire against pavement; $F_x = \mu_x F_z$	lbs [N]
FY or F_y	Lateral (cornering) force developed by rolling tire (the component of the resultant force perpendicular to the camber axis, and lying in the ground plane); $F_y = \mu_y F_z$	lbs [N]
FZ or F_z	Normal force on tire	lbs [N]
g	Regression exponent of X_6	-
h	Regression exponent of X_7	-
H1	Longitudinal force transducer reading (in space fixed coordinates) from low speed tire tester	V or lbs [N], dep. on context

i	Regression exponent of X_8	-
j	Regression exponent of X_9	-
k	Regression exponent of X_{10}	-
l	Regression exponent of X_{11}	-
L1, L2	Lateral force transducer readings (in space fixed coordinates) from low speed tire tester	V or lbs [N], dep. on context
m	Regression exponent of X_{12}	-
M_D, M_R, M_F	Masses of driver, rear wheel/frame, and front wheel/fork, respectively, in motorcycle simulation.	slugs [kg]
n	Regression exponent of X_{13}	-
N	Number of data points	-
p	Regression exponent of X_{14}	-
PF	Pavement factor; $PF \equiv X_{10}$	-
q	Regression exponent of X_{15}	-
r	Rolling radius of tire	in. [cm]
R^2	Correlation coefficient	-
S	Standard deviation; $S=[(N\Sigma X^2-(\Sigma X)^2/(N(N-1))]^{1/2}$	
SN_{20}	Pavement ASTM skid number at 20 mph	-
TF1	(Tire Factor 1);$\equiv X_5$	-
TF2	(Tire Factor 2);$\equiv X_9$	lb/deg-lb [N/deg-N]
TF3	(Tire Factor 3);$\equiv X_{14}$	-
V	Wheel velocity	mph [km/h]
V1, V2, V3, V4	Vertical force transducer readings (in space fixed coordinates) from TTI low speed tire tester	Units may be volts (v) or lb [N] dep. on context
X, Y, Z	Body fixed coordinates in motorcycle simulation	in [cm]

X', Y', Z'	Space fixed coordinates in motorcycle simulation	in. [cm]
X", Y", Z"	Front fork coordinates in motorcycle simulation	in. [cm]
X_1	Sideslip angle (regression model); $X_1 = \alpha$	degrees
X_2	Camber angle (regression model); $X_2 \equiv \gamma$	degrees
X_3	Grooving approach angle (regression model; $X_3 \equiv AA$	degrees
X_4	Normal load (regression model); $X_4 \equiv FZ$	lbs
X_5	Maximum lateral friction coefficient (cornering regression model); $X_5 \equiv \mu y_{max}$	-
X_6	Groove width (regression model)	in.
X_7	Groove depth (regression model)	in.
X_8	Groove spacing (regression model)	in.
X_9	Cornering coefficient (cornering regression model); $X_9 \equiv C_\alpha$	lb/deg-lb
X_{10}	Pavement factor; $X_{10} = SN_{20}/100$	-
X_{11}	Reference tire force (lateral or circumferential regression model, depending on context); force developed on ungrooved pavement; $X_{11} \equiv F_R$	lbs
X_{12}	Circumferential slip in percent (braking regression model)	-
X_{13}	Velocity (regression model); $X_{13} \equiv V$	mph
X_{14}	Maximum circumferential friction coefficient (braking regression model); $X_{14} \equiv \mu x_{max}$	-
X_{15}	Circumferential slip coefficient (braking regression model)	lb/(%)(lb)
Z_i	Statistical submodel i for F_G (contains a subset of the variables X_1 through X_{15})	lbs

α	(In Appendix B only) Level of significance; α=.05 in this study	-
γ	Tire inclination (camber) angle; $\gamma \equiv X_2$	degrees
δ	Steer angle of motorcycle front wheel about steer axis	radians
θ_F	Rake angle of motorcycle steer axis	radians
μ	Friction coefficient; friction force ÷ normal force	-
μ_y, μ_x	Friction coefficients in side and circumferential directions	-
ω	Rotational velocity of tire	sec^{-1}

CONVERSION UNITS

The units of measurements in this report are in the English system. The conversion factors for the SI system of units are listed below.

1 in	=	2.54 cm
1 in^2	=	6.45 cm^2
1 ft	=	.3048 m
1 ft-lb	=	14.593 N-m
1 lb	=	.4536 kg
1 lb/in	=	175.12 N/m
1 lb/in/sec	=	175.12 N/m/sec
1 lb/in^2	=	6.895 kN/m^2
1 $lb/in/sec^2$	=	1.152 $kg/cm/sec^2$

GENERAL INTRODUCTION

It is quite apparent that pavement grooving in some form is becoming widely accepted as a means of improving the skid resistance of existing pavements. In general, highway grooving in the United States is primarily longitudinal, whereas on aircraft runways and in other countries such as England the emphasis is on transverse grooving. Appendix A contains a comprehensive annotated literature survey of pavement grooving.

For a given pattern, various dimensions of the groove width, depth and spacing have been studied; however, an optimum pattern has not been accepted. Most studies of highway grooving have relied on measurements on in-service roadways. Factors such as skid numbers, texture or surface wear, and accident rates were investigated on a "before grooving" and "after grooving" basis. To a limited extent, driver response and vehicle behavior have been monitored, primarily by public response.

When grooves were first introduced, a large number of complaints were filed by motorcycle riders with the state highway departments and motorcycle magazines [1]. These riders claimed that the grooved pavements produced uncomfortable riding that could be hazardous. Experience has shown that the effects of grooving on motorcycles vary with the width of the grooves. Eugene Farnsworth of the California Division of Highways and a noted authority on pavement grooving states that 1/4 in. wide grooves generated complaints from motorcyclists and drivers of small cars. The 1/8 in. wide grooves still brought complaints from motorcyclists although there were fewer [1, 2]. In addition, these narrower grooves were just as effective in controlling skids as the wider grooves. At the beginning of this research, the complaints of motorcycle riders were thought to be a phenomenon of "cyclic interlock" or the "path of least resistance". Cyclic interlock was believed to consist of an interlock or engaging and disengaging of the tire tread ribs and the pavement grooves. Thus, as small discontinuous forces were encountered as the result of cyclic interlock, a compensating rider response would be required. These resulting periods of unbalance would be extremely unsettling to the rider. With the path of least resistance, the self-aligning torque induced by the grooved pavement opposes normal gyroscopic steering movement of the front wheel. The cyclist finds himself in an unfamiliar position of having to apply steer forces to the handlebar properly coordinated with his shift in body weight. Appendix C contains a few of the letters containing complaints received from approximately 50 motorcycle riders throughout the country.

This report presents the findings of a study that involved laboratory and full-scale tests. These tests employed various groove geometries and pavements and considered the effects of slip, camber and approach angles, normal load, tire geometry, pavement, speed, groove geometry, and wet or dry conditions. The data were collected using the Texas Transportation Institute's (TTI) low speed tire tester and the Highway Safety Research Institute's (HSRI) mobile tire tester. Figure 1 illustrates some of the equipment and facilities used in the study.

Since the advantage of grooved pavement under rainfall conditions is thoroughly documented both directly, through its capability for producing larger values of lateral friction, and indirectly through highly significant reductions in accidents, and is the real basis for the implementation of grooving pavements, this study was not primarily concerned with contributing to that body of data but placed its primary emphasis upon the determination of vehicle handling or stability problems on dry pavements. The portion of the study which resulted in the wet pavement data was very much a sidelight undertaken because the process was readily available, and not because it was considered the best approach to accumulate wet pavement data. Consequently, a "wet" pavement will merely refer to a pavement with a particular skid number as obtained by the HSRI tester. This is emphasized by the fact that the truck-borne water systems used produced lower friction levels, but not levels low enough to be consistent with rain wetted surfaces [3, 4].

Free rolling and braking data were taken with each machine. The data were next used as input to a regression model that produced a functional relationship for the grooved side or circumferential force in terms of the variables mentioned previously. These representations for the free-rolling and braking cases were next integrated with handling computer programs for automobiles, motorcycles and articulated vehicles.

Initially, only low speed data taken with the TTI tester had been compiled. Later, it was decided to include high speed data in the models and consequently the HSRI mobile tire tester was employed. This tester was not able to accommodate the motorcycle tire, hence only automobile tires were considered.

A regression analysis was performed resulting in a model which produced results consistent with data found in the literature. The trends were quite realistic. These findings are presented in Chapter IV.

The conclusions presented in a later section are based upon contact with leading researchers in the field, automobile driver and motorcycle rider evaluation of grooved pavements, laboratory and full-scale test data and computer simulation.

FIGURE 1: EQUIPMENT AND FACILITIES USED IN STUDY

Chapter I
EXPERIMENTAL APPROACH

Laboratory and full-scale vehicle data were compiled in the study. The laboratory data were taken with the TTI low speed tire tester and the HSRI mobile tire tester. The full-scale tests were performed by employing a motorcycle instrumented to measure steering angle and steering torque and also an automobile-towed vehicle combination. Some of the tires used in the study are shown in Figures 2-5.

The study considered the effects of the following variables:

1. slip angle - angles of 4°, 8°, 16° were employed for the automobile and trailer tires and angles of 0° and 6° for the motorcycle tires.
2. camber angle - angles of 0°, 5°, 10° for the automobile and trailer tires and angles of 0°, 20°, 40° for the motorcycle tires.
3. approach angle - angles of 0°, 10°, -10°, 45°, 90° for both the automobile and motorcycle tires were included.
4. load - values of 650 lbs, 900 lbs, 1400 lbs for automobile and trailer tires, 200 lbs and 400 lbs for motorcycle tires, and 400 lbs for the trailer tire.
5. tire - the following tires were used:

   <u>Automobile</u>:

   G 78-14 Goodyear Custom Power Cushion (rated load of 1620 lbs @ 32 psi)

   7.50 x 14 General ASTM (rated load of 1085 lbs @ 24 psi)

   5.60 x 15 Goodyear Custom G8 (rated load of 970 lbs @ 32 psi)

   <u>Motorcycle</u>:

   3.50 x 18 Trials knobby tire*

   3.00 S-18 Dunlop Gold Seal F-7*

   3.50 S-18 Dunlop K-95*

---
*Recommended maximum load not listed

FIGURE 2 STANDARD RIBBED F7 DUNLOP MOTORCYCLE FRONT TEST TIRE

FIGURE 3 K-95 DUNLOP MOTORCYCLE
REAR TEST TIRE

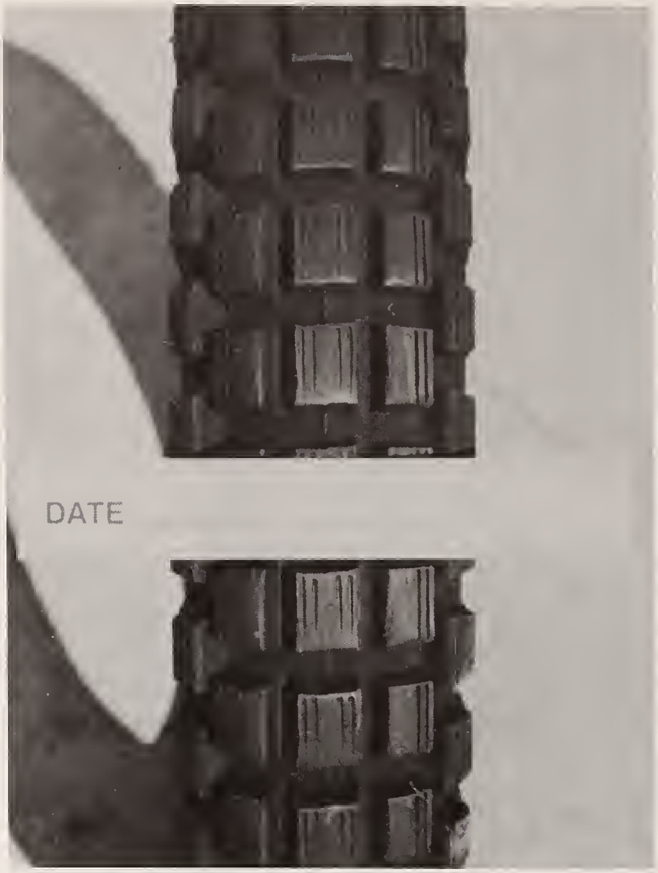

FIGURE 4 KNOBBY MOTORCYCLE TEST TIRE

FIGURE 5 GOODYEAR 480-400-8" TRAILER TEST TIRE

Small Trailer:

4.80 x 4.00 x 8 Goodyear Super Rib*

The effect of various tires was accounted for through the use of $(\mu_y)_{max}$ and $(\mu_x)_{max}$, i.e., the ratio of the peak side (free rolling) or circumferential (braking) force to the normal wheel load and through the use of a tire cornering or camber coefficient. For the free rolling cases the tire coefficient was computed as the slope of the side force vs. slip angle (for automobile and trailer tires) or camber angle (for motorcycle tires) evaluated at zero slip angle, divided by the normal load. For the braking cases, the coefficient is the slope of the braking force vs. % slip at zero slip, divided by load.

6. groove width - groove widths of .110", .125" and .220" were considered. The pavement surfaces used in the low speed laboratory tests employed all three widths, whereas the full-scale tests and the data taken with the HSRI mobile tire tester only considered the .110" width. Only one blade width was used to perform the grooving for the full-scale tests.
7. groove depth - data for groove depths of 1/8", 1/4", and 3/8" were collected. The low speed testing considered all three depths, whereas only 1/8" depth was employed in obtaining the full-scale data.
8. groove spacing - groove spacings of 3/4", 1", and 1-1/2" were used. The low speed test data used all three values while the full-scale results included only 3/4" and 1".
9. speed - the low speed tester used a speed of 2.25 mph only. The full-scale tests taken by the HSRI tester employed speeds of 20 and 40 mph.
10. pavement factor - the effect of the various pavements was accounted for through the use of the locked wheel skid number

*Recommended maximum load not listed

obtained with the Goodyear Custom Power Cushion G 78-14 tire for the data collected with the HSRI tester and the skid number using the 7.50 x 14 ASTM E-249 tire at 2.25 mph for the low speed data.

The surfaces that were used for the full-scale testing were grooved by Pavement Specialists, Inc., Dallas, Texas and consisted of four sections, two straight and two curved. The straight sections were of Portland Cement Concrete (PCC) (160' x 36') and asphaltic concrete (160' x 24'), respectively. The grooves were cut longitudinally and were .110" x 1/8" x 1". The curved sections were approximately 300' x 22', had a radius of curvature of approximately 350', featured longitudinal .110" x 1/8" x 3/4" grooves, and consisted of Portland Cement and asphaltic concretes, respectively. These surfaces are shown in Figures 6-9.

The laboratory testing performed with the TTI low speed tester employed slabs approximately 6' long, 2' wide and 2" deep. Longitudinal, transverse, and 10°, 45°, -10° skewed geometries were evaluated. Groove geometries of .110" x 1/8" x 1", .110" x 1/8" x 3/4", 1/8" x 3/4", 1/8" x 1/8", 1", .220" x 1/4" x 1-1/2" were included. Both Portland Cement and asphaltic concrete slabs were grooved.

Initially, some shifting in the tire forces was noticed. To circumvent this the tires were shoulder worn and the pavement surfaces were "broken in" by exposing them to a series of trial runs. This procedure eliminated most of the variation and ensured more reliable results. Due to the large amount of data required, only one run was made for each data point.

The HSRI mobile tire tester was employed in taking the braking data. In developing μ_x (circumferential force/normal load) versus slip and μ_y (side force/normal load) versus slip angle, several runs were taken to develop a data point. This number varied from two to as many as 13, and the final value was the average of the number of runs required to produce consistent results. A summary of the testing and simulation conducted is shown in Table 1.

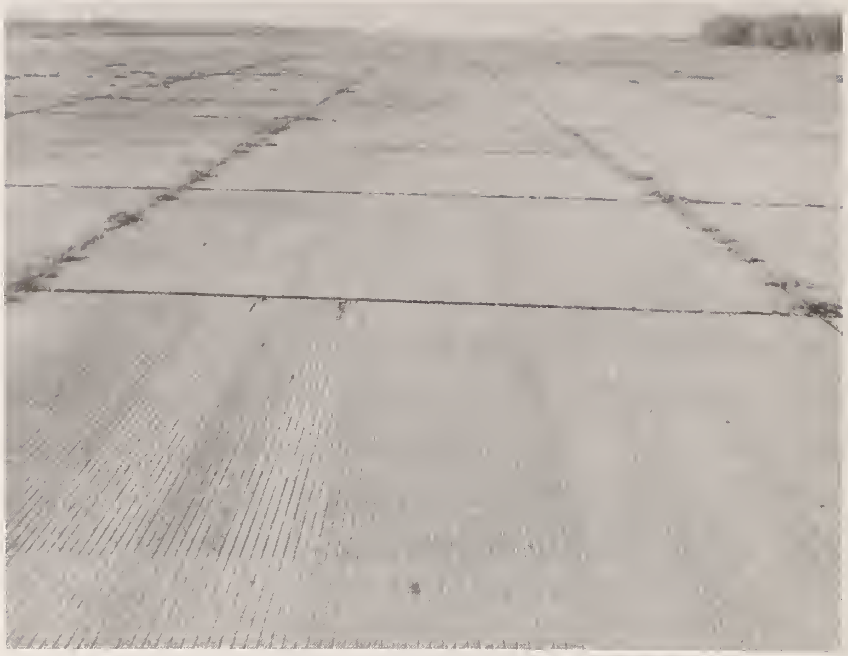

FIGURE 6: STRAIGHT PORTLAND CEMENT CONCRETE SURFACE

FIGURE 7: STRAIGHT ASPHALTIC CONCRETE SURFACE

FIGURE 8: CURVED PORTLAND CEMENT CONCRETE SURFACE

FIGURE 9: CURVED ASPHALTIC CONCRETE SURFACE

TABLE 1. SUMMARY OF TESTING AND SIMULATION.

TESTS / VARIABLE	TIRE	GROOVE GEOMETRY			PAVEMENT		VEHICLE PARAMETERS (Speed, load, slip and camber angles)
		Long.	Transverse	Skewed	Asphalt	Concrete	
Automobile							
a. Full Scale							
b. Laboratory	X	X	X	X	X	X	X
c. Computer Simulation (constant steer maneuver)		X		X		X	
Motorcycle							
a. Full Scale*	X	X	X	X	X	X	X
b. Laboratory	X	X	X	X	X	X	X
c. Computer Simulation (maneuver, see Chapter V)		X		X		X	X
Automobile/Towed Vehicle							
a. Full Scale	X	X		X	X	X	X
b. Laboratory	X	X	X		X	X	X
c. Computer Simulation (maneuvers, see Chapter V)		X		X	X	X	X

*Instrumented and from rider evaluation

The cornering data (for the grooving equation) obtained with the HSRI tester was extracted from the braking runs. The data obtained with this tester consistently showed the smooth pavement or reference lateral force to be larger than the grooved pavement force. The cornering data taken with the HSRI tester had a significant influence upon the cornering model, an influence now believed to be inappropriate. For this reason, two cornering models were developed, one including the high speed data and the other excluding it. The cornering values predicted by the equation which includes the high speed lateral force data indicates a trend that seems contrary to some of the published literature [5].

The reason the high speed cornering data is believed to be unreliable is due to the manner in which it was taken. These data were collected over a pavement length of approximately 160 ft. However, circumferential slips varying from free-rolling (0%) to fully locked (100%) are included in a run. The 0° data represents the average value taken over a very small distance, approximately the first 2 ft, a distance insufficient to generate the available lateral force. Thus, it is believed that reliable free-folling values of lateral force were not obtained from the braking data. The braking results, however, have been carefully evaluated and are believed to be of acceptable accuracy.

Chapter II
FULL-SCALE VEHICLE TESTING

Motorcycle Testing

A preliminary motorcycle test was conducted at the TTI Research Annex on the grooved pavements. The test employed a 1974 Yamaha RD 350 motorcycle having a standard ribbed Dunlop front tire and Dunlop K-87 rear tire. The test used an uninstrumented motorcycle and was conducted to evaluate the pavement grooving from a rider's viewpoint. The specifications for the motorcycle are given below:

Specification for Motorcycle

Displacement:	347 cc
Bore and Stroke:	64 x 54 mm
Horsepower:	39 bhp @ 7500 rpm
Torque:	28 ft. lbs. @ 7000 rpm
Transmission:	six speed
Compression ratio:	6.6 x 1
Weight:	315 lbs. (dry)
Wheelbase:	52 in.
Ignition:	battery, 12 volt

Three riders were selected: one inexperienced, one average, and one highly-skilled. The highly-skilled rider was a professional with considerable experience, the average rider had approximately two years experience on dirt and street riding, whereas the inexperienced rider, the principal investigator of the research project, had less than one year's experience on street riding only.

The inexperienced and average riders rode the grooved surfaces at speeds up to 70 mph while the highly-skilled rider was allowed to ride at speeds exceeding 70 mph. Most of the riding was done on the Portland Cement Concrete curve having a radius of approximately 350 ft. and being 300 ft. long and 22 ft. wide. The grooves on the surface are .110" x 1/8"

X 3/4". The maneuvers consisted of in-lane and lane-change travel. The three riders agreed that at speeds below 50 mph there was no noticeable effect on the handling. At speeds above 50 mph but below 60 mph a slight wobble was detected when no attempt to follow the grooves was made. This wobble appeared to be eliminated, however, when an effort was made to follow the grooves. At speeds between 60 mph and 70 mph the consensus was that a perceptible wobble was present when not following the grooves, but only a very slight wobble was evident when attempting to follow the grooves. At speeds exceeding 70 mph, the skilled rider reported a hazardous feeling when not attempting to follow the grooves on the curve and a disconcerting feeling when trying to follow the grooves. Since the evaluation was based upon a curved portion that had newly-cut grooves, it was decided to perform another series of tests for straight portions and pavements with worn grooves. In order to accomplish this, permission was obtained from the Texas Highway Department District Office in San Antonio, Texas, to use part of the grooved section of freeway on Loop 410 in San Antonio. The stretch of roadway used involved the east and west-bound lanes of Loop 410 between the Blanco Road exit on the east and the Fredericksburg exit on the west. This constituted approximately four miles with no sharp curves. The only rider used for these tests was the project's principal investigator. The motorcycle was the same one that had been previously used for the tests at the TTI Research Annex. A TTI vehicle equipped with a motion picture camera followed the test vehicle in an attempt to photograph any wobble that might be caused by the grooved pavement.

The movie camera was not able to pick up any wobble of the motorcycle as it travelled on the grooved pavement. Runs with speeds well exceeding the legal speed limit of 55 mph were made when safe traffic conditions were present and a hazardous condition or feeling was never observed. In fact, the effect of the grooves only manifested itself by a slight vibration that was felt through the seat. This feeling was only encountered at the higher speeds. At the lower speeds no effect was detected whether trying to follow the grooves or when performing a lane change maneuver. However, it must be emphasized that the grooves were worn and not nearly as sharp edged as the ones that had been used in the first tests.

Following the testing in San Antonio, it was decided to purchase a set of Trials Universal tires (semi-knobby) and use them on the test motorcycle, a 1974 Yamaha. These tires are stock items on dual purpose motorcycles that are used for street and dirt riding. An evaluation of the grooved pavements at the TTI facilities with these tires ensued.

The rider for the tests with the Trials tires was the project's principal investigator. The speeds were kept well below 65 mph. For speeds approaching 55 mph and making no attempt to follow the grooves, a perceptible wobble was felt. At speeds near 65 mph, a disconcerting feeling was experienced. However, it must be mentioned that the tires were new, and the previous tests on these pavements had employed worn street tires. Also, the semi-knobby tires produce a different motorcycle handling response than street tires and it was the test rider's first experience with these tires.

Later a study with worn semi-knobby tires was conducted. The handling of the motorcycle with worn tires was compared to the handling response that had been obtained with new tires. It appeared that higher speeds (above 65 mph) could now be attained on the grooved pavements before a disconcerting feeling was experienced. This effect may be partially due to the rider becoming accustomed to the semi-knobby tires.

In addition to the testing with the Trials tires on grooved pavements, some riding was done on pavements with a metal tine texture. These surfaces are often mistaken for grooved pavements by motorists so testing was done to compare the effects of the two surfaces. The riding was done with both street and semi-knobby tires. The metal tine texture definitely produced a more uncomfortable feeling than the grooving. The motorcycle had a tendency to drift, even at speeds below the legal speed limit of 55 mph. At higher speeds the effect was more pronounced and a slight wobble appeared. For some instances, it appeared that the motorcycle had a tendency to follow the wavy pattern of the metal tine texture and perhaps some "cyclic interlock" was taking place. For other instances the tendency was for the motorcycle to drift across the lane of travel. In the presence of a strong cross wind and heavy traffic, a hazardous condition could arise.

Riding at Dallas Love Field was done by the project's principal investigator on the test Yamaha RD 350 motorcycle. The riding was done with and without a steering damper. Riding over transverse grooves on PCC pavement (1/4" x 1/4" x 1-1/4") did not produce an uncomfortable effect for speeds up to 75 mph. The longitudinal and angle runs could not be made for extended lengths since the runways were grooved transversely and the approach had to be made from a taxiway. These runs also showed little if any effect for speeds up to approximately 55 mph but it is felt that the distance considered was inadequate.

On the return trip to College Station some riding was also done on some grooved PCC pavement on IH 45 in Navarro County near Angus, Texas. The grooved portion was approximately one-half mile long and was considered adequate for test purposes. Several runs with and without a steering damper were made. At speeds below 55 mph no disturbing effect with or without the damper was noticed. At higher speeds a noticeable wobble that seemed to increase with speed was observed when no steering damper was used. Once the wobble was developed it remained present until the speed was reduced to approximately 50 mph. In addition, the vibration phenomenon did not appear to manifest itself immediately at any one speed, but instead seemed to take approximately 100-200 ft to develop, depending on the speed.

From the runs made in Navarro County, pavement grooving definitely affects motorcycle handling, and the effect depends on the physical properties of the motorcycle. The wobble encountered cannot be considered hazardous, in the opinion of the principal investigator, except to a very unskilled rider. However, strong feelings to the contrary have been voiced by members of the motorcycling fraternity (See Appendix C).

The findings of the subjective motorcycle study conducted in Navarro County for the purpose of performing the roadway disturbance analysis were successful; at least from a rider evaluation point of view. The longer distance of approximately 1/2 mile gave the disturbance more time to manifest itself and significant differences between grooved and ungrooved pavements were experienced.

In Navarro County, the full-scale test data included motorcycle steering torque and steering angle time histories over the segment of grooved pavement. The test speeds varied from 40 mph to 75 mph. Data from the angle and torque transducers were telemetered to a mobile base station where it was recorded on FM analog magnetic tape and simultaneously displayed on visicorder paper.

Unfortunately, inspection of raw signals for grooved pavement showed no startling differences from those of ungrooved pavement, although the driver experienced a very perceptible difference. The use of these signals as input to the CALSPAN motorcycle simulation is presented in a later chapter.

The analog test tapes were digitized and appropriate scale factors were determined from the transducer calibration signals which were also placed on tape. Digitizing was performed at the rate of 1000 samples/sec, or over five times the frequency of the raw signal. This is a standard practice for any digitized data. These runs were approximately thirty seconds in length which resulted in about 30,000 words of digitized information per transducer channel per file (test run). From this TTI generated a second digital tape with information in engineering units and reduced to a manageable length of about six seconds per run. Four of these runs were put on this edited tape version, and sent to CALSPAN for use as input to the motorcycle simulation model. These four runs included: 1) an ungrooved pavement run for baseline purposes; 2) a run on grooved pavement with bike steering damper in place; 3) a corresponding run with damper removed; and 4) a run on grooved pavement with damper removed, at a higher tire pressure.

Instrumented Trailer Testing

A full-scale test involving a 1972 Volkswagen and a six foot trailer was conducted at the TTI Research Annex to determine the effects of the pavement grooving on the response of the automobile-trailer combination. The specifications for the automobile are given below:

Curb weight	1960 lbs
Weight distribution front/rear	43/57%
Wheel base	94.48 in.
Width	61 in.
Length	159.8 in.
Height	59.1 in.
Tires (stock)	6.00-15

Initially the trailer has a dry weight of 750 lbs and a tongue load of 88 lbs. Later, additional weight was placed in the trailer to bring the total weight to 900 lbs but the tongue load was reduced to 20 lbs. The lower tongue load was used in an effort to provide a less stable ride and hopefully to be better able to detect the effects of the grooving. According to Bundorf [6] a rearward center of gravity location can enhance trailer oscillation to the point of instability. A tongue load of 12 to 15% of the gross trailer weight was recommended to bring the trailer center of gravity forward of the axle. It was felt that if the ride were unstable and the grooves tended to stabilize it, the instrumentation might provide more meaningful data traces; also, if the grooves had a detrimental effect, the driver would be able to detect the increased instability.

A rotary variable differential transformer (RVDT) was attached to the frame of the vehicle with its shaft fixed to the trailer hitch by means of a flexible cable. Use of the cable provided a measure of the relative raw angle between the vehicle and the trailer and cancelled the effects of any angular changes in the <u>outer</u> planes. The RVDT was excited by a precision regulated voltage and its output monitored by a thermal strip-chart recorder.

Initially, testing was conducted without the recording equipment being turned on in order to obtain a feel for the stability of automobile-trailer system. The trailer load was 750 lbs and the tongue load was 88 lbs. Later, the sand bags that were placed in the trailer to bring the load to 900 lbs were shifted in order to produce a different tongue load. Runs were made on the straight portions of grooved concrete which had .110" x 1/8" x 1" grooves and on a grooved 350 ft radius curve having .110" x 1/8" x 3/4" grooves. Runs were made at speeds of 30 mph, 40 mph, and 50 mph. At all three speeds the automobile-trailer system was extremely stable and no detrimental effects due to the grooving were experienced. At 50 mph, however, a sensation of slight vibration in the steering wheel was evident. This vibration was not present when a similar run was made on ungrooved pavement.

The instrumented runs were made with a 900 lbs total load and a tongue load of 20 lbs. The cases considered involved runs on the straight and curved portions of grooved concrete at speeds of 30 mph, 40 mph, and 50 mph. The relative yaw angle data traces revealed that the instrumentation could not detect any difference between grooved and ungrooved pavement response. All the traces were consistent in showing no effect. From the tests conducted, it is indicated that pavement grooving does not have any detrimental effects on small automobile-towed vehicle combinations. Even though testing of larger vehicles and different load combinations was not performed, it is felt that one of the more typical small car-towed vehicle combinations was tested. This combination should be more susceptible to the effect of pavement grooving than heavier car-trailer systems.

Chapter III
THEORETICAL APPROACH

In the present study a comprehensive set of data was compiled and a statistical regression analysis was employed to extract from the data, the main features of the relationships. For any system, there may in fact be a simple functional relationship between variables; however, often there appears to exist only a relationship which is too complicated to grasp or to described in simple terms. Appendix B presents a basic discussion of the assumptions made in a regression and correlation analysis of the type performed in this study.

Usually, a "good" regression model or equation in the view point of a practical engineer, requires: (a) a simple expression, (b) high multiple correlation, (c) small prediction error, and (d) satisfaction of all physical constraints. A "Two-step Constrained Selection Regression Methodology" [7] was employed to analyze the data. The method requires two successive regression analysis steps. Regression models, sub-models and variables are selected based on user-oriented decisions subject to physical constraints.

The first step in this method is essentially a selection regression procedure [8, 9] using a multiplicative model in order to obtain the approximate exponents of each individual independent variable. The results of the first step of the regression procedure are several sub-models, which are selected based on criteria (b), (c), and (d) of the previous paragraph. The second step determines the coefficients of linear combinations of the intermediate products. The final model is selected from these linear combinations based upon the four criteria mentioned previously.

The full model is of the form:

$$F_G = e^a X_1^b X_2^c X_3^d X_4^e X_5^f X_6^g X_7^h X_8^i X_9^j \ldots X_{15}^q \tag{1}$$

Equation (1) represents the full model (containing all variables). Sub-models contain subsets of the independent variables. Physical constraints on the models can be met with suitable signs for the regression exponents. For example, if an exponent is positive, then F_G will increase as the factor with that exponent increases. The investigator must decide whether the sign of an exponent in the sub-model is representative of the physical problem. The sub-models deemed unrealistic are rejected; those retained are further tested for a high coefficient of multiple correlation and low standard error. The sub-model in the set

$$Z_i = f\ (X_1\ X_2\ \ldots\ X_{15})$$

are combined linearly to provide the model which is used for the second step regression:

$$F_G = b_0 + b_1\ Z_1 + b_2\ Z_2 + \text{--}\ b_n\ Z_n$$

Several such models are actually used, one for each possible combination of the b_i. For large i, the number of models could be large, but for only three submodels Z_i there are just seven to consider:

$$
\begin{array}{lllllll}
\text{Model 1} & F_G = b_{01} & + b_{11}\ Z_1 & + b_{21}\ Z_2 & + b_{31}\ Z_3 \\
\text{Model 2} & F_G = b_{02} & + b_{12}\ Z_1 & + b_{22}\ Z_2 & \\
\text{Model 3} & F_G = b_{03} & + b_{13}\ Z_1 & & + b_{33}\ Z_3 \\
\text{Model 4} & F_G = b_{04} & & + b_{24}\ Z_2 & + b_{34}\ Z_3 \\
\text{Model 5} & F_G = b_{05} & + b_{15}\ Z_1 & & \\
\text{Model 6} & F_G = b_{06} & & + b_{26}\ Z_2 & \\
\text{Model 7} & F_G = b_{07} & & & + b_{37}\ Z_3
\end{array}
$$

Taking into account the four selection criteria mentioned earlier in this chapter, a "good" model is selected from among the seven.

At times the second step regression procedure was not necessary because an initially high R^2 value resulting from the first step regression was readily acceptable. In these circumstances a Statistical Analysis System (SAS) [10] one step regression was used.

Four separate equations were developed; three for automobile tires and one for motorcycle tires. The automobile formulae consider free-rolling and braking cases, whereas the motorcycle equation only predicts free-rolling effects. The formulae from equation (1) are as follows:

$$F_G = e^a X_1^{\,b} X_2^{\,c} X_3^{\,d} X_4^{\,e} X_5^{\,f} X_6^{\,g} X_7^{\,h} X_8^{\,i} X_9^{\,j} X_{10}^{\,k} X_{11}^{\,l} X_{12}^{\,m} X_{13}^{\,n} X_{14}^{\,p} X_{15}^{\,q} \qquad (2)$$

where the values of the exponents are presented in Table 2. The numbers in the first column represent the exponents that are used to predict the grooved side force on an automobile tire when the high speed HSRI cornering data are used, those in the second column the values when the HSRI high speed data are neglected, those in the third column for the prediction of the automobile circumferential tire force due to the grooves, and those in the fourth the grooved side force on a motorcycle tire. The simple statistics of these equations are presented in Appendix B.

The computer simulation was carried out by using three distinct vehicle handling computer models. They included an automobile handling program, HVOSM [11], a motorcycle handling program developed by CALSPAN Corp. [12], and a program for articulated vehicles developed by the Highway Safety Research Institute (HSRI) [13]. These programs incorporated the grooving model power laws presented here.

The automobile handling program was modified by TTI in order for it to accept the pavement grooving modification. The modification was quite extensive and is presented in Volume II a separate report of this study.

The modification to the motorcycle handling program was performed by CALSPAN Corporation and all computer runs were made at their facilities. This code had been proprietary until recently and at the present time an adequate user's manual does not exist. It is anticipated that the original program without the grooving modification will be made available through

TABLE 2: EXPONENTS FOR GROOVING POWER LAWS

	CAR Free-Rolling*	CAR Free-Rolling**	CAR Braking	MOTOR-CYCLE Free-Rolling
Constant Factor	$e^{.3278}$	$e^{-.3467}$	$e^{.0207}$	$e^{.6381}$
X_1 (sideslip angle)	.04477	.1658	-.0113	-.0116
X_2 (camber angle)	-.00379	-.0151	-.0318	-.0124
X_3 (approach angle)	.0002691	.0018	-.0223	.0307
X_4 (normal load)	.01089	.2889	-.0178	-.0671
X_5 (max. lateral friction)	.08664	.2634	0.0	.0175
X_6 (groove width)	.06838	-.0842	-.2044	0.0
X_7 (groove depth)	-.01991	-.0270	-.0234	0.0
X_8 (groove spacing)	-.2095	0.0	0.0	0.0
X_9 (corner coeff.)	-.008096	.0438	0.0	.0874
X_{10} (SN 20/100)	.002626	-.0276	.3319	-.2618
X_{11} (ref. force [ungrooved])	.9637	.6821	.9793	1.0095
X_{12} (% circ. slip)	0.0	0.0	.0620	0.0
X_{13} (velocity)	-.06929	0.0	-.0429	0.0
X_{14} (max. Long. friction)	0.00	0.0	-.7722	0.0
X_{15} (circ. slip coeff.)	0.00	0.0	.2062	0.0

* Contains HSRI free-rolling high speed data
** Contains no high speed data

another contract to DOT in the near future. The report submitted by CALSPAN Corporation, including the description of the computer program, is presented in Appendices E and F.

The articulated-vehicle computer program that predicts the grooving response for automobile-towed vehicle systems was modified by HSRI. This program is proprietary; consequently, the parametric studies and all computer runs were made at the HSRI facility.

Chapter IV
VALIDATION OF SINGLE TIRE MODEL AND PARAMETER STUDIES

This Chapter discusses the validation of the cornering and braking models for grooved pavements based upon: (1) a single tire computer model that employs the HVOSM algorithm and (2) comparison between measured results and results obtained by substituting into the grooving power laws. In addition, parameter variations obtained using the single tire program are presented and discussed.

In order to abstract the behavior of the empirical grooved-pavement models from the dynamic effects of the full HVOSM vehicle simulation, the single tire program mentioned in the first paragraph was built around the HVOSM subroutines INPUT, DAUXR, TIRFR, and INTPR. A pair of subprograms were added to evaluate the grooved pavement forces in the circumferential and lateral directions. These subprograms employed the same grooving function obtained from the regression analysis and later used by HVOSM in order to simulate the grooving effects. With this type of simulation parameters such as velocity, sideslip and camber angles, circumferential slip, etc., can be set to specific values independently of each other, making it easy to see the effects of each factor in the grooving formulas.

The validation study for the grooved pavement models, both cornering and braking, used a series of low speed (2.25 mph) and higher speed (20 and 40 mph) experimental data. The low speed data was taken by TTI's low speed tester, for tire side forces developed due to changes in sideslip angle, camber angle, approach angle, normal load, pavements and groove geometry. The higher speed measurements were taken by the HSRI mobile tire tester and consisted of braking forces due to effects of pavement, speed, normal load, sideslip angle and circumferential slip. In all the tests, both smooth and grooved pavements were used, the smooth being used as the reference, or control pavement.

To check the accuracy of the grooving functions (Chapter III, equation 2), the ratio of the grooved-pavement force (F_G) to the reference smooth-pavement force (F_R) was introduced. The experimentally determined F_R values were then used as input variables to the grooving equations and the predicted grooved force and in turn the predicted ratio F_G/F_R were produced. The predicted F_G/F_R values were compared with the actual F_G/F_R data obtained from the tests as is shown in Figure 10. This plot indicates that the model gives fairly good agreement with the test data and shows that the effect of the grooves appears more beneficial at the higher slip angles or near the point of peak friction. The difference between predicted and measured results is in most cases within one standard deviation as reported in Appendix B.

The results of the grooving equation for braking are illustrated by Figure 11. This figure shows a typical case, a G78 tire on "wet" concrete (SN=56) at 40 mph and 1400 lb normal load. Here, the grooving effect for circumferential (braking) forces shows a marked increase over the force developed on reference pavement. As before, the measured reference force was used with the predictor model and all model parameters were set to match the experimental conditions. The model's prediction was accurate for circumferential slips below 20% but was optimistic at the higher slips. It should be mentioned that the data were collected in increments of 2% up to a circumferential slip of 20% and in increments of 5% from 20% to 100%, thus biasing the results towards the lower circumferential slip. The lower values, however, are more typical of "real world" situations. Figure 11 also shows that the measured grooved and reference forces are the same at approximately 100% slip indicating that for this case the grooves do not give an increase in the braking force at full lock-up. The maximum effect of the grooves is obtained near peak braking at approximately 20% circumferential slip for this case.

The braking equation showed a high correlation (R^2=.903) but the standard deviation (111.18 lbs) indicated a large amount of variation in the data base. Since the standard deviation was larger than one might expect for this high correlation, the data were analyzed for the error

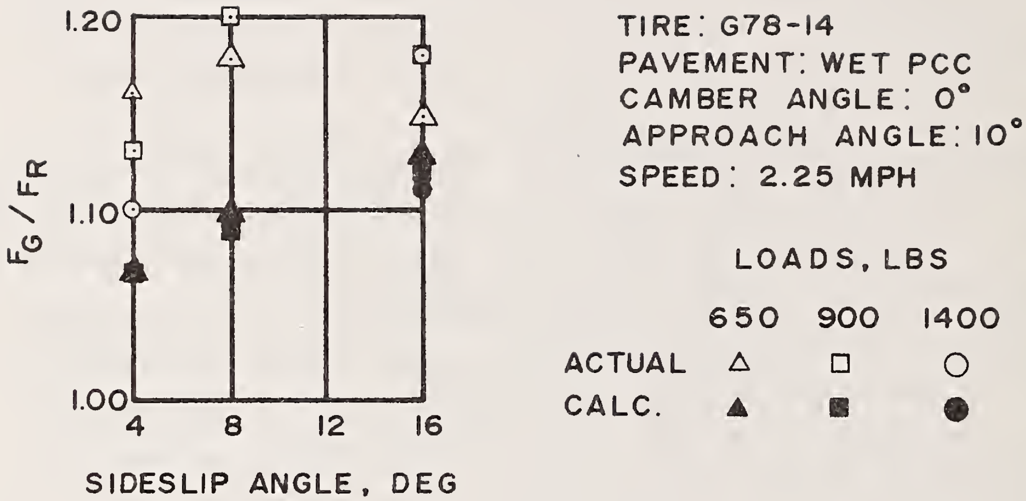

FIGURE 10: GROOVING SIDE FORCE - REFERENCE SIDE AS MEASURED AND AS PREDICTED BY GROOVING MODEL (HSRI.- SINGLE TIRE).

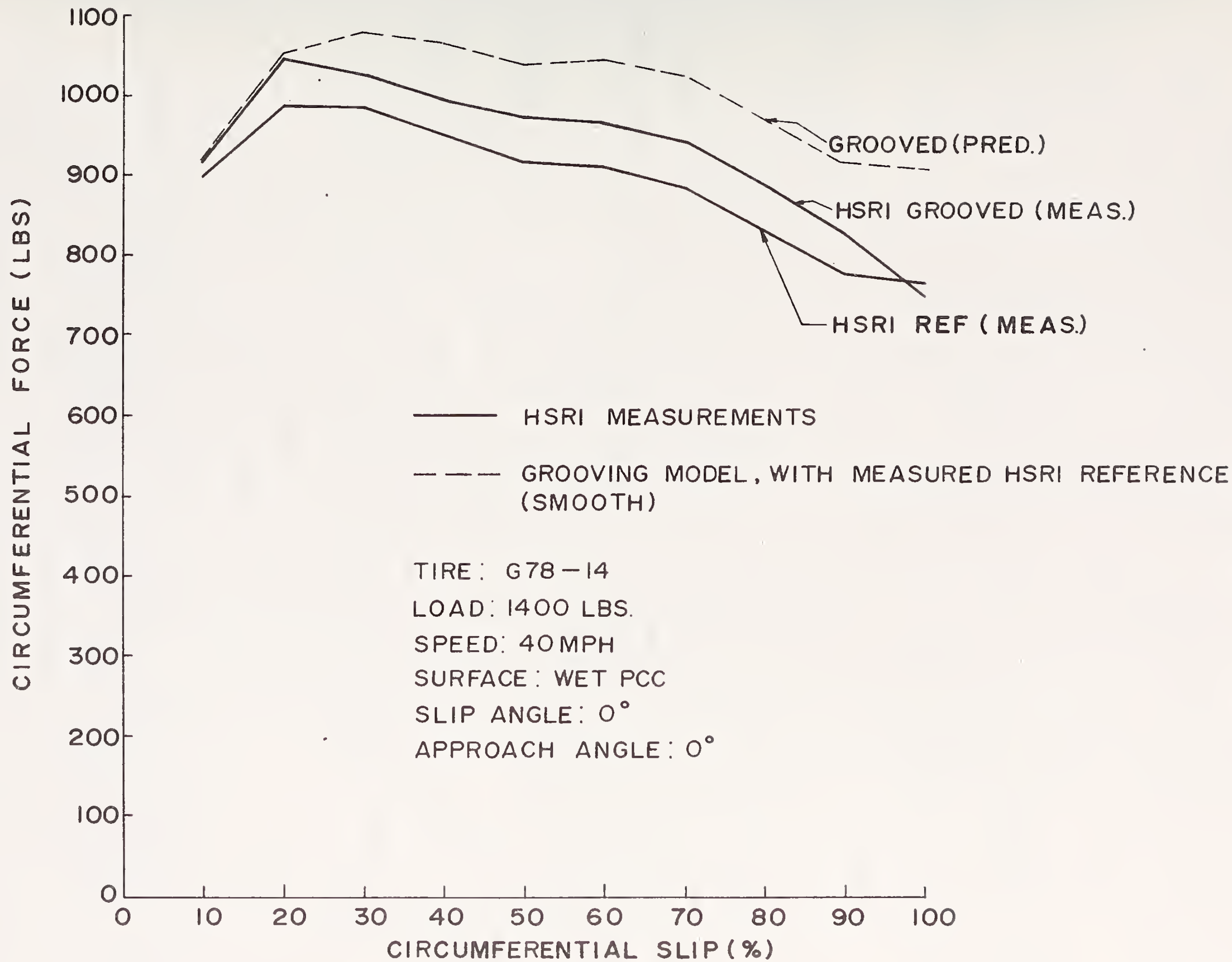

FIGURE 11: CIRCUMFERENTIAL FORCE AS FUNCTION OF CIRCUMFERENTIAL SLIPPAGE.

being of a random nature. The data were subjected to the Durbin-Watson test for autocorrelation and the results indicated in influence of an unidentified variable(s). This unidentified variable(s) could be due to intertire or pavement variability that was not accounted for.

Figure 12 presents the results obtained from the single tire model that uses a computed reference (smooth pavement) force obtained from the HVOSM algorithm. The plot indicates that the grooved lateral force is greater than the smooth force for all the speeds considered. The curves were drawn for a skid number of 60 which is close to the "wet" value obtained from the HSRI tester that employs internal wetting.

Figure 13 illustrates the benefit of grooving for skid numbers from 20 to 80, according to the model. It reflects the widely experienced fact that grooving is of greatest benefit on slippery pavements.

Figure 14 represents a plot of the lateral force as a function of the sideslip angle. The curves indicate that grooving produces increased skid resistance as the sideslip angle increases. It should be emphasized that data were not collected past a 16° sideslip angle and the plot represents an extrapolation of the data collected.

Figure 15 depicts the relationship between lateral force and grooving approach angle. The curves show that grooving produces an increased lateral resistance over the smooth pavement; however, based upon the data collected, the effect of the grooving approach angle is not significant.

The braking parameter variations were carried out at a constant 30% circumferential slip while the effects of changing speed, normal load, and skid number were investigated. In general, grooving appears to have a favorable effect on braking forces under the conditions investigated. Figure 16 is a graph of the difference between reference and grooved braking forces with speed. Figure 17 shows the difference with normal load. Both indicate an increase in the braking force, primarily at low speeds and high normal loads. It should be emphasized that there were no data collected past 40 mph and Figure 16 is based upon an extrapolation and hence the higher speed results should be interpreted with caution. Figure 18 shows how the pavement skid number affects braking forces.

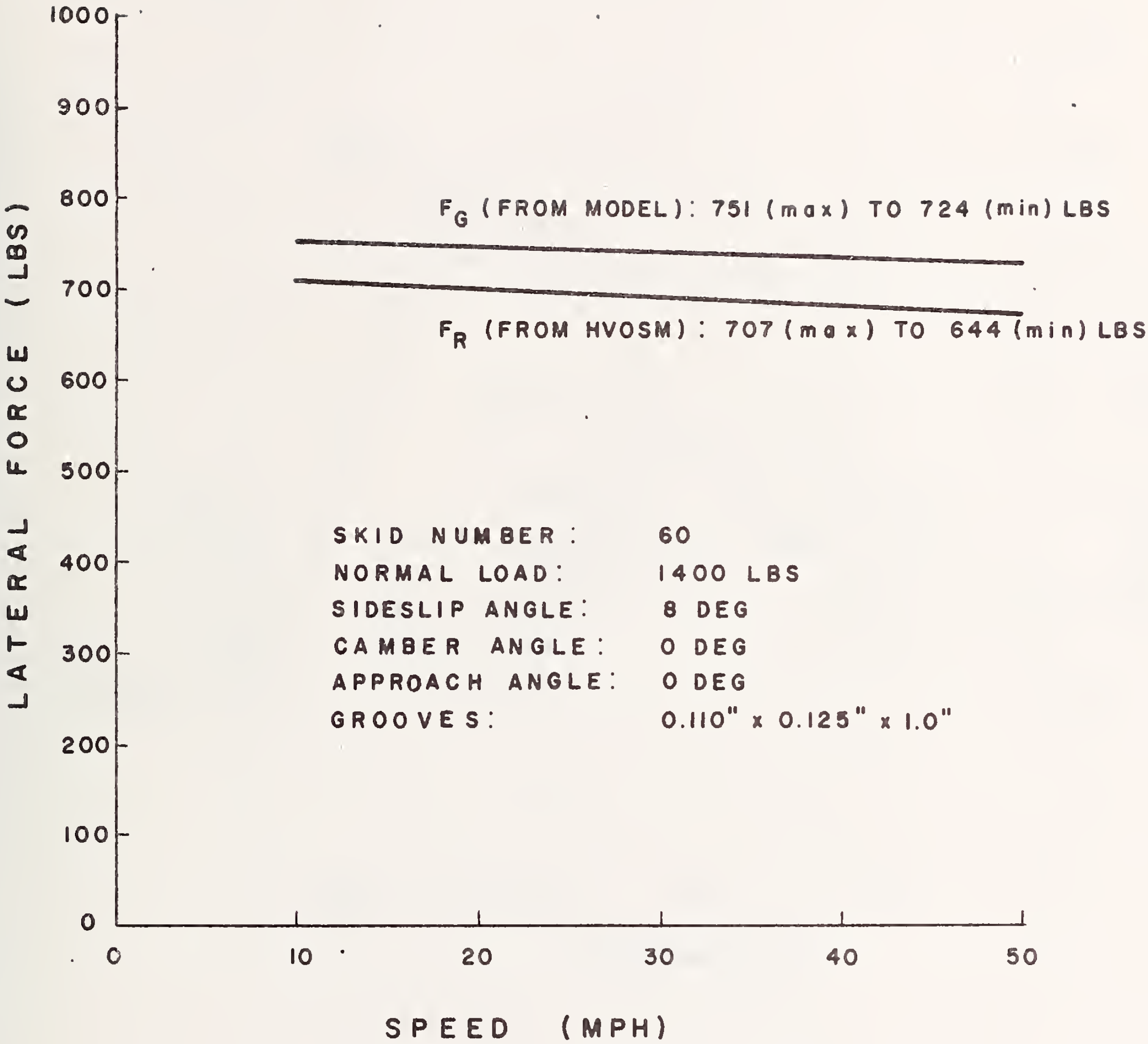

FIGURE 12: BEHAVIOR OF LATERAL FORCE MODEL USING SINGLE-TIRE HVOSM REFERENCE FORCE AS INPUT, SHOWING ROAD SPEED DEPENDENCE.

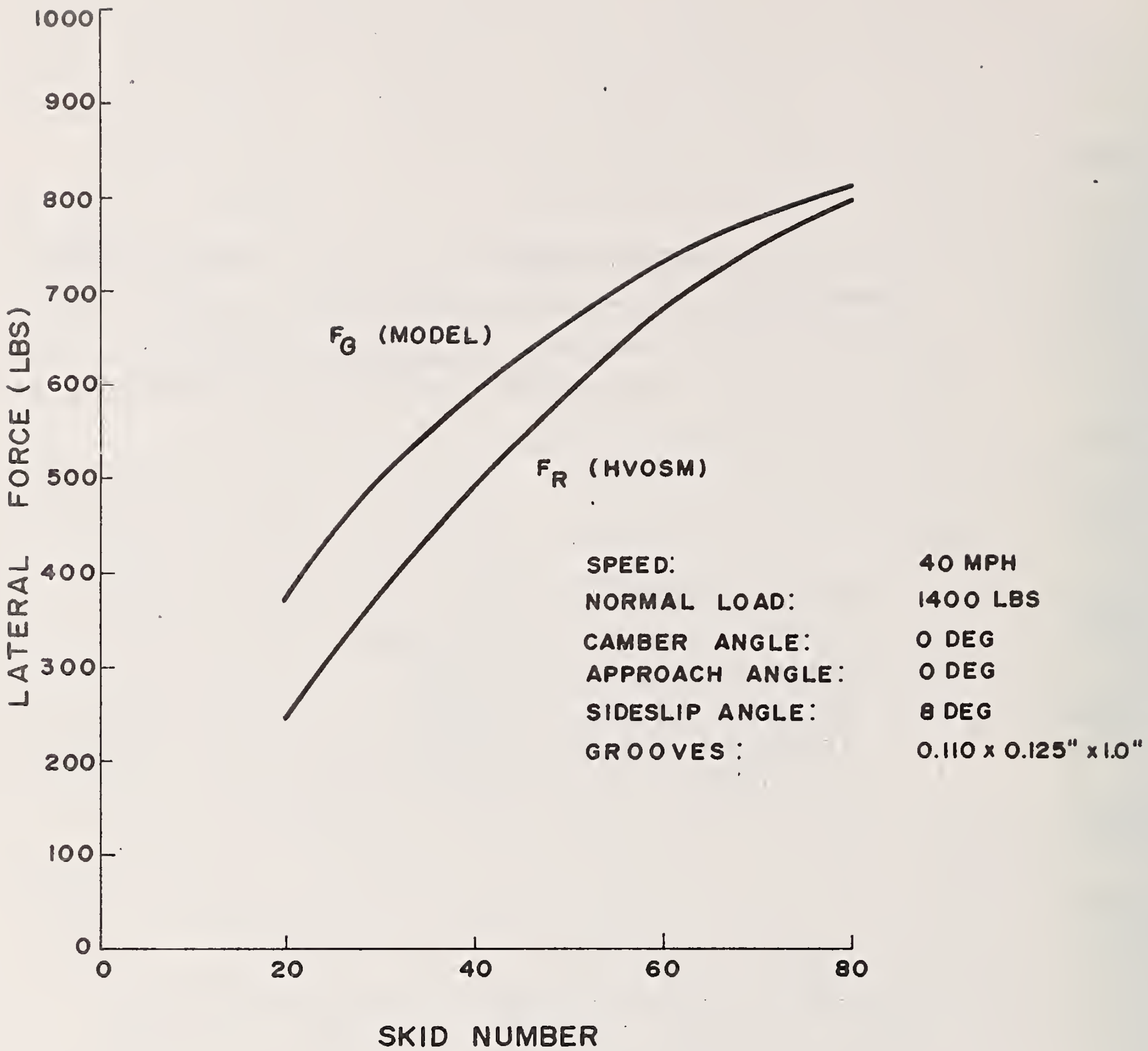

FIGURE 13: BEHAVIOR OF LATERAL FORCE MODEL USING SINGLE TIRE HVOSM REFERENCE FORCE AS INPUT, SHOWING SKID NUMBER DEPENDENCE.

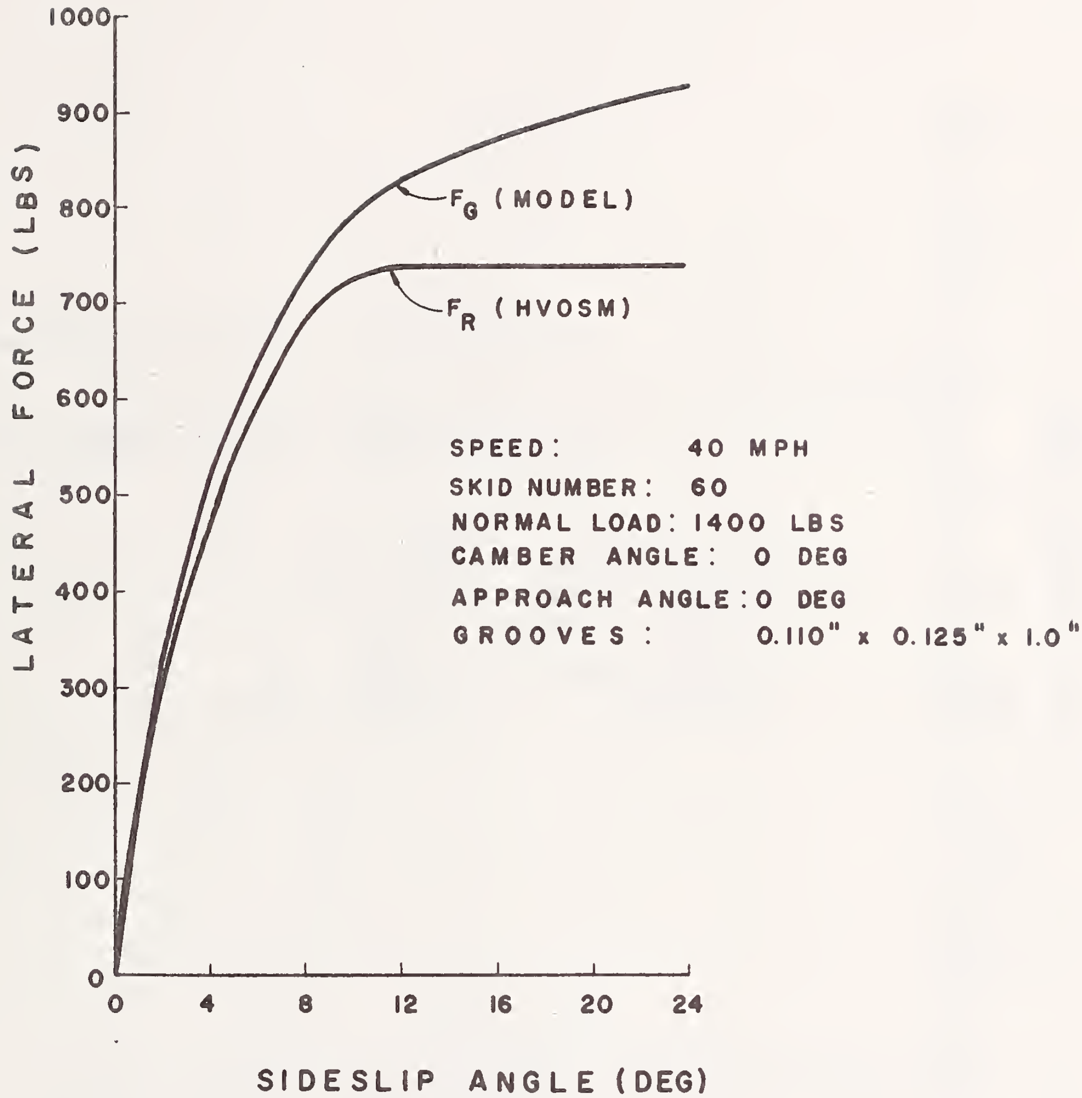

FIGURE 14: BEHAVIOR OF LATERAL FORCE MODEL USING SINGLE-TIRE HVOSM REFERENCE FORCE AS INPUT, SHOWING SIDESLIP ANGLE DEPENDENCE.

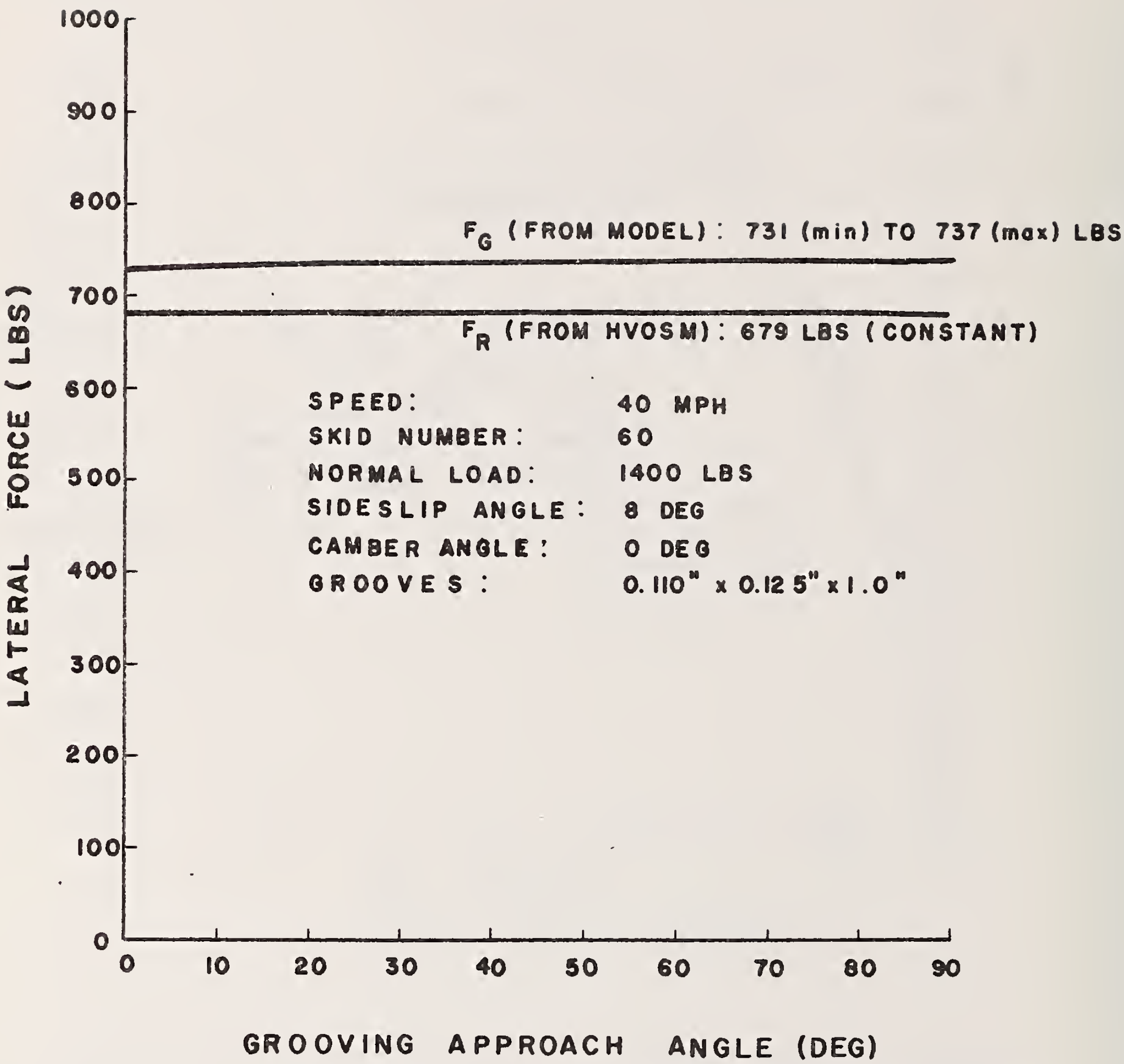

FIGURE 15: BEHAVIOR OF LATERAL FORCE MODEL USING SINGLE-TIRE HVOSM REFERENCE FORCE AS INPUT, SHOWING APPROACH ANGLE DEPENDENCE.

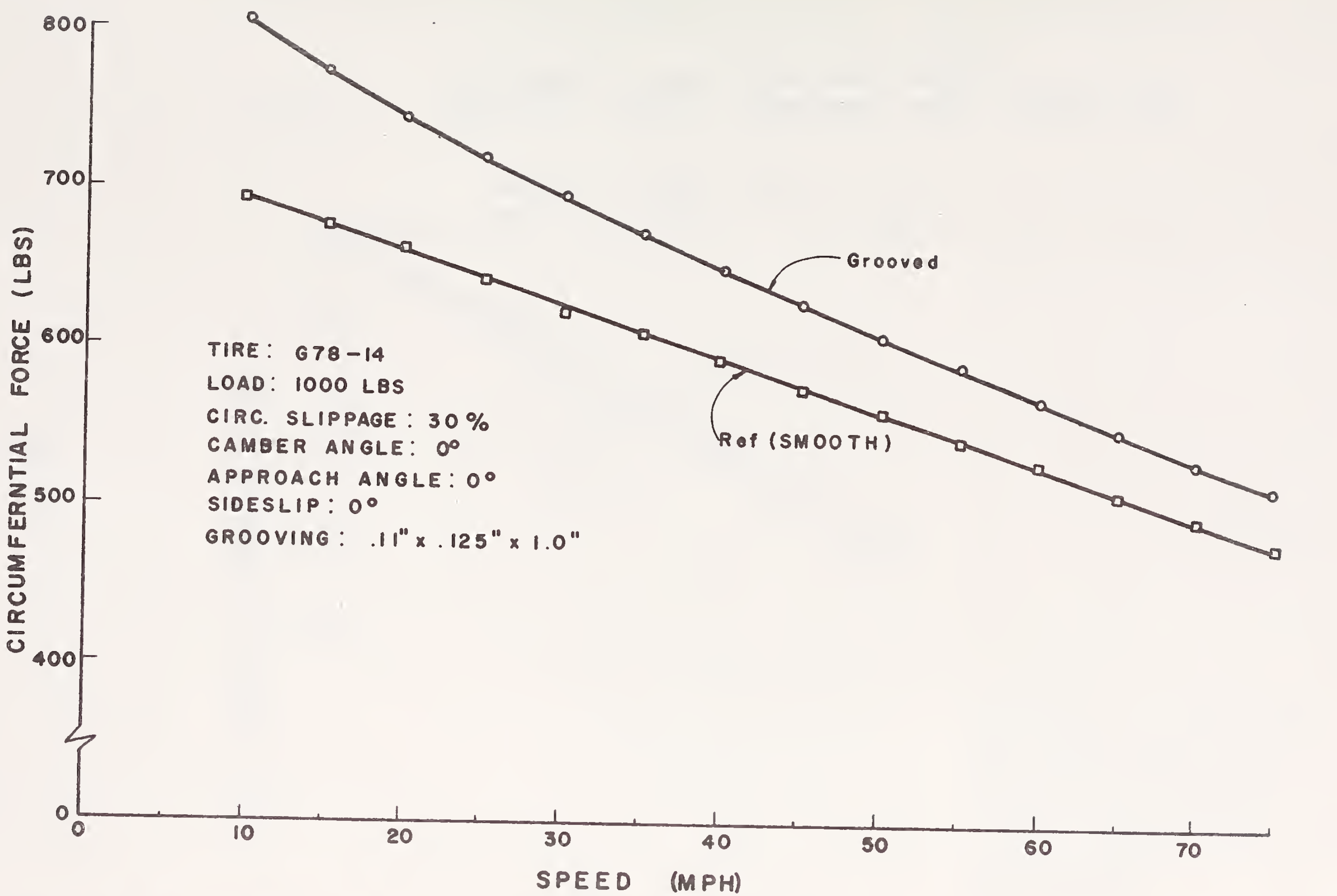

FIGURE 16: BRAKING FORCE vs. SPEED PREDICTION BY SINGLE TIRE GROOVING MODEL.

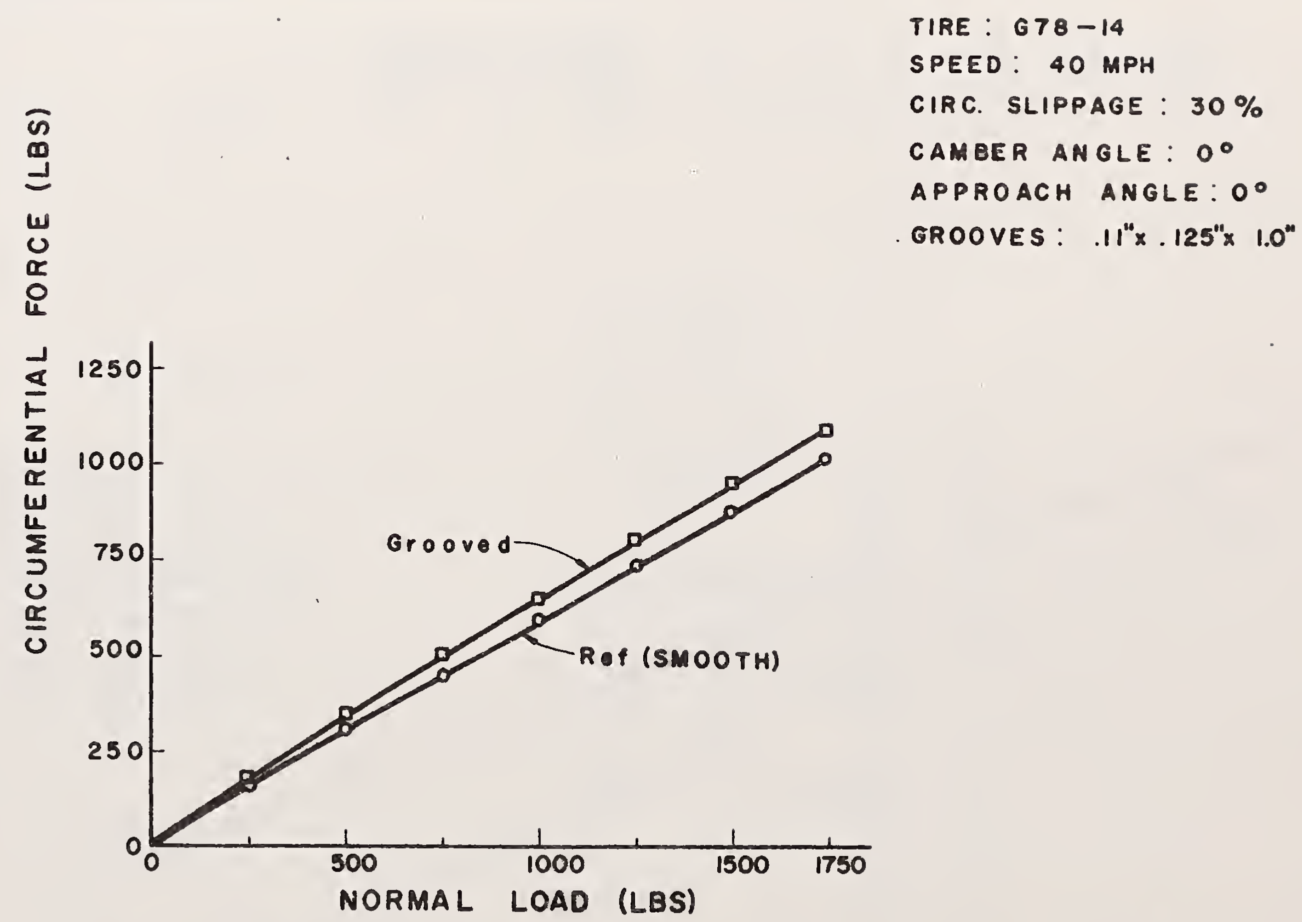

FIGURE 17: BRAKING FORCE – NORMAL LOAD PREDICTION BY SINGLE TIRE GROOVING MODEL.

Overall, there is a general increase of braking force with SN when the range of the variables falls within the limits of the data collected. For SN values less than 56 there were no data collected, hence the results plotted in Figure 18 represent an extrapolation. Since it is known that grooving provides beneficial effects on lower friction pavements, it appears that for this case, the model may not provide meaningful results when it is used to predict grooving forces outside the range of the data it is based upon. Thus, the extrapolated results shown in this figure should not be construed as an actual trend but rather as insight into what to expect from the model in its present stage of development.

It should be emphasized that this chapter was included merely to show that the grooving models are able to predict the field data and also to demonstrate some of the results that may be expected when certain variations among the parameters are performed. The grooving functions are based upon a regression analysis of the test data. Hence, the results obtained will reflect any limitations of the data base. However, it should be mentioned that the basic ground work for the prediction of pavement grooving effects through the use of a mathematical model has been established. The model, as has been pointed out, can be enhanced through the use of a larger data base.

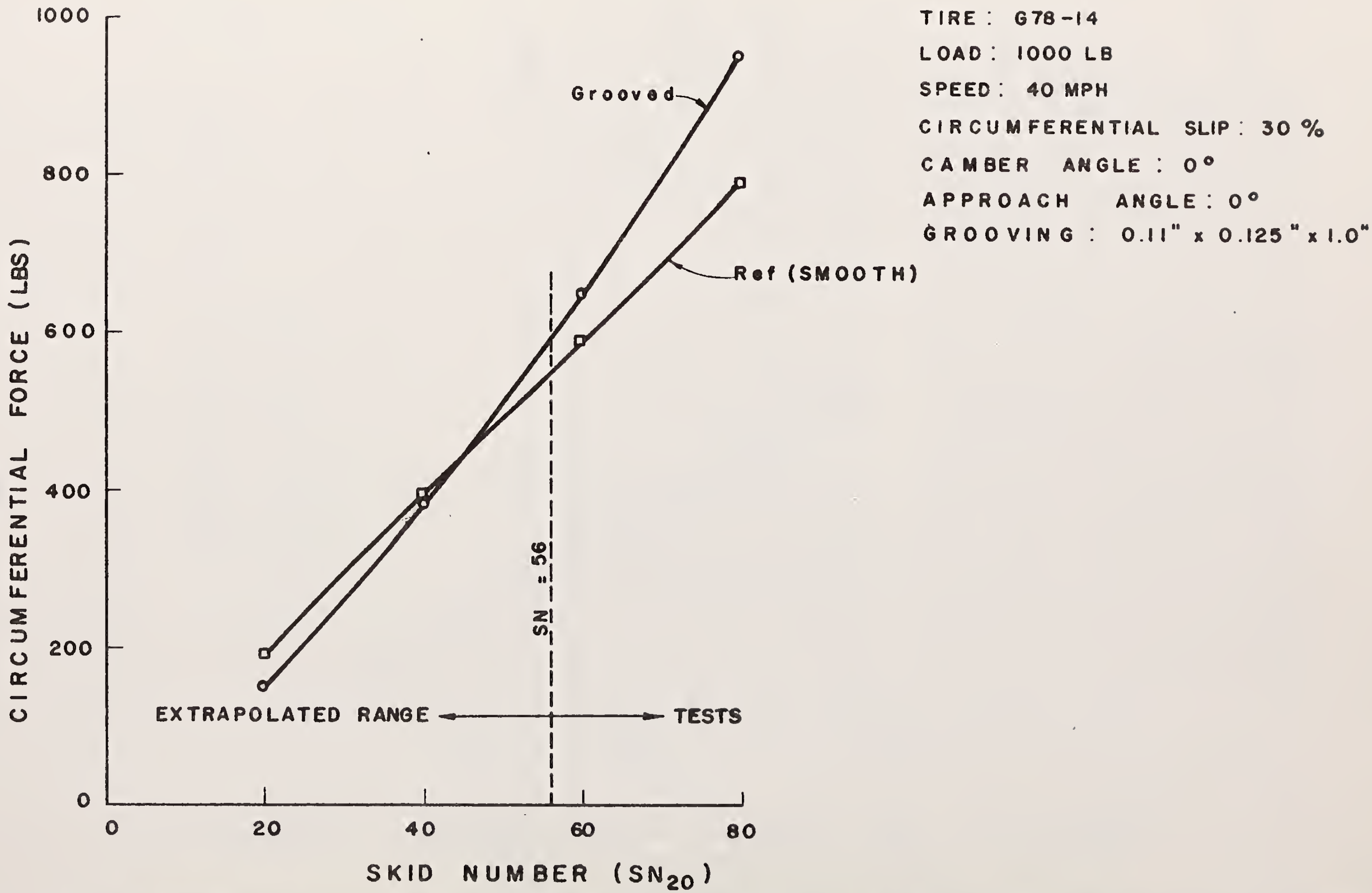

FIGURE 18: BRAKING FORCE vs. SKID NUMBER PREDICTION BY SINGLE TIRE GROOVING MODEL.

CHAPTER V

DISCUSSION OF RESULTS

The results obtained by the HSRI computer simulation of an articulated vehicle in the free-rolling and braking conditions on both grooved and smooth (ungrooved) pavements are illustrated in this section. The results of simulated maneuvers on smooth pavements closely match test results obtained by HSRI on a TTI test pad using a new B.F. Goodrich Silvertown Belted E78-14 tire inflated to 24 psi [14]. The grooved road simulation results also compared closely to the same tests. This simulation incorporated the first tire/grooved pavement force regression equation, the equation based on both TTI low speed and HSRI high speed data which was previously discussed in Chapter I.

Three kinds of calculations were made:

1. Runs with nonzero initial articulation angles, the so-called NZA maneuvers;
2. J-turn maneuvers; and
3. Lane change or sinusoidal steer maneuvers.

The parametric data describing the vehicle and trailer used in all these runs are given in Table 3. Table 4 presents the data used for the regression model. The free-rolling simulation used is described in Reference 13 whereas the braking model is described in Reference 15.

The NZA maneuvers are presented in Figures 19-22. There are four curves in each figure -- a smooth road run and a grooved road run for initial articulation angles of 2.5° and 5°. As one would expect, based on the similarity of the first tire force regression equations for smooth and grooved road conditions, similar results are computed for smooth and grooved roads.

The J-turn maneuvers are presented in Figures 23-26. In each case, the steer angle was increased linearly for the first second of the run, then held constant. Again, smooth and grooved road results are markedly similar.

TABLE 3: VEHICLE DATA FOR SIMULATION
SYSTEM OF AUTOMOBILE - TRAILER

INPUT PARAMETER TABLE

NO.	SYMBOL	DESCRIPTION		INITIAL VALUE
01	GVW1	WT. OF TRACTOR (LBS)		3660.00
02	GVW2	WT. OF TRAILER (LBS)		2106.00
03	IZZ	TRACTOR MOM. OF INERTIA (IN-LB-SEC--2)		27380.90
04	ITZZ	TRAILER MOM. OF INERTIA (IN-LB-SEC--2)		50781.90
07	A1	DIST. FROM TRACTOR CG TO FRONT AXLE (IN)		48.30
08	A2	DIST. FROM TRACTOR CG TO REAR AXLE (IN)		60.70
09	A3	DIST. FROM TRAILER CG TO FIFTH WHL (IN)		108.20
10	A4	DIST. FROM TRAILER CG TO AXLE (IN)		17.80
11	BB	DIST. FROM TRACTOR REAR SUSPENSION TO FIFTH WHL (IN). FIFTH WHL LOCATED AFT OF SUSPENSION IS POSITIVE.		36.00
12	TRA1	HALF LAT. DIST. BETWEEN CENTERS OF TIRE CONTACT ON TRACTOR FRONT AXLE (IN)		30.75
13	TRA2	HALF LAT. DIST. BETWEEN CENTERS OF TIRE CONTACT ON TRACTOR REAR AXLE/S (IN)		30.75
14	TRA3	HALF LAT. DIST. BETWEEN CENTERS OF TIRE CONTACT ON TRACTOR AXLE/S (IN)		30.75
15	Z0	HEIGHT OF FIFTH WHL ABOVE GROUND(IN)		17.10
16	Z1	HEIGHT OF TRACTOR CG ABOVE GROUND (IN)		20.40
17	Z2	HEIGHT OF TRAILER CG ABOVE GROUND (IN)		36.10
18	MU5	FIFTH WHEEL FRICTION COEFFICIENT		0.0
19	RAD5	EQUIVALENT RADIUS OF FIFTH WHEEL (IN)		19.00
20	GAM1	PORTION OF TOTAL LAT. LOAD TRANSFER ON FRONT AXLE OF TRACTOR		0.62
23	VEL	INITIAL VELOCITY: U-DIRECTION (MPH)		30.00
			(FPS)	44.00
24	TIMF	MAX. SIMULATION TIME FOR THIS RUN (SEC)		8.00
25	IQUIT	MAX. ARTICULATION ANGLE ALLOWED (DEG)		30.00
	CALF (1-10)	CORNERING STIFFNESS OF TIRES (LBS/DEG)		
29			CALF (1)=	133.70
30			CALF (3)=	132.30
31			CALF (7)=	144.80
	MUP (1-10)	PEAK TIRE-ROAD FRICTION COEFFICIENT		
32			MUP (1) =	0.93
	MUS (1-10)	SLIDING TIRE-ROAD FRICTION COEF.		
35			MUS (1) =	0.86
	SP (1-10)	SLIP CORRESPONDING TO PEAK MU		
38			SP (1) =	0.25

TABLE 4

DATA FOR TTI REGRESSION MODEL FOR CORNERING

$e = 0.3278$

$X_1 = 0.04477$

$X_2 = -.00379$

$X_3 = 0.0002691$

$X_4 = 0.01089$

$X_5 = 0.08664$

$X_6 = 0.06838$

$X_7 = -0.01991$

$X_8 = -0.2095$

$X_9 = -0.008096$

$X_{10} = 0.002626$

$X_{11} = 0.9637$

$X_{13} = -0.06929$

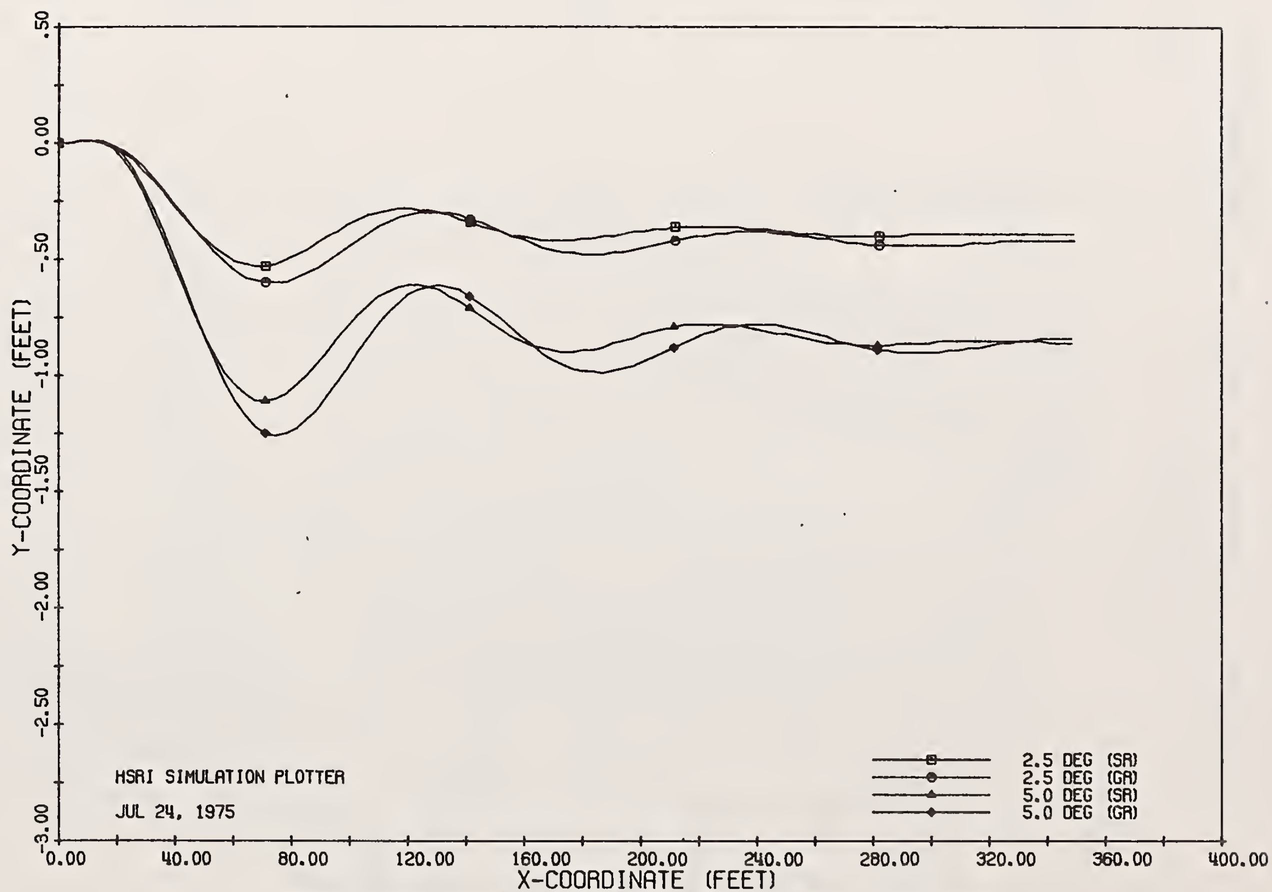

FIGURE 19 MUSTANG-TRAILER,30 MPH,GAMMA(0) VARIED,SMOOTH OR GROOVED ROAD(SR OR GR)

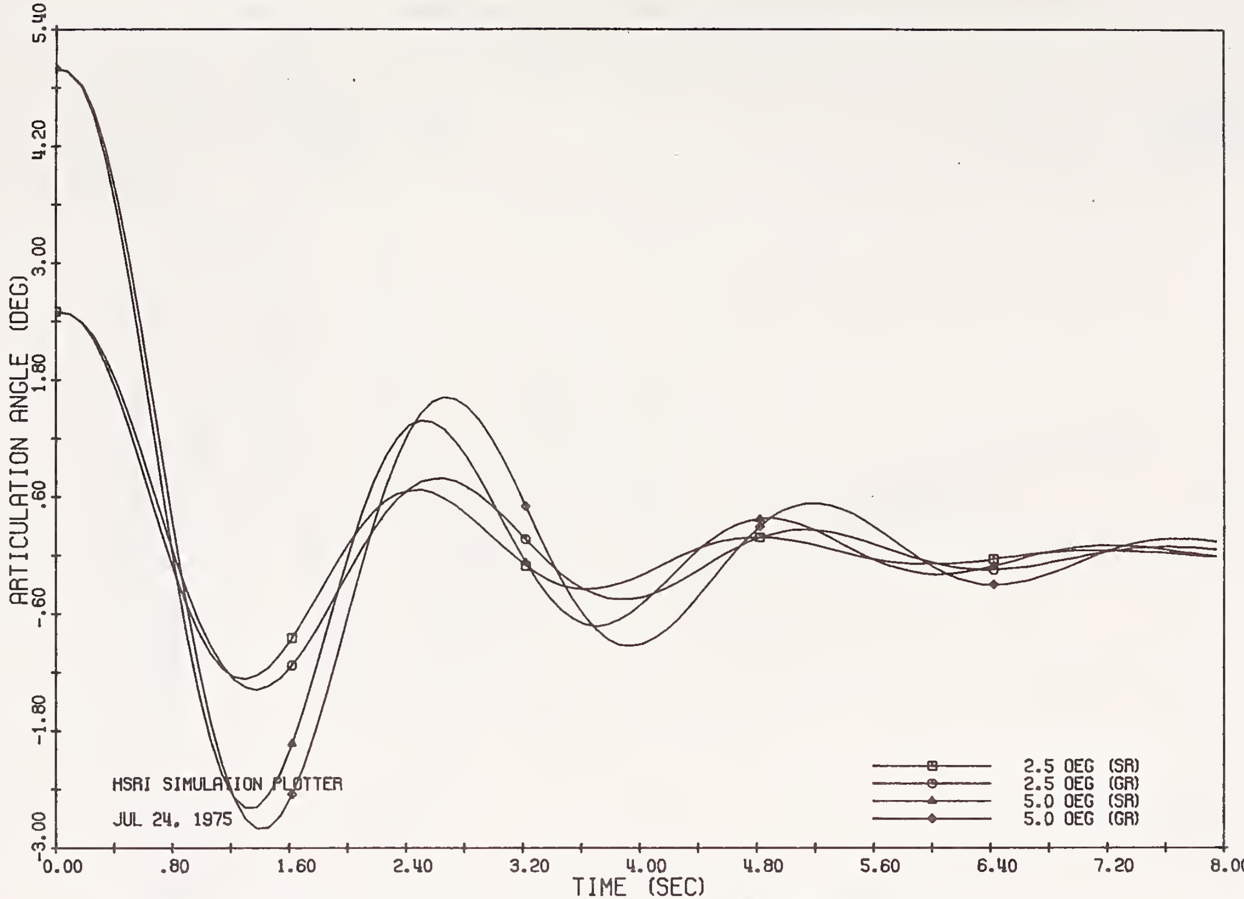

FIGURE 20 MUSTANG-TRAILER, 30 MPH, GAMMA (0) VARIED, SMOOTH OR GROOVED ROAD (SR OR GR)

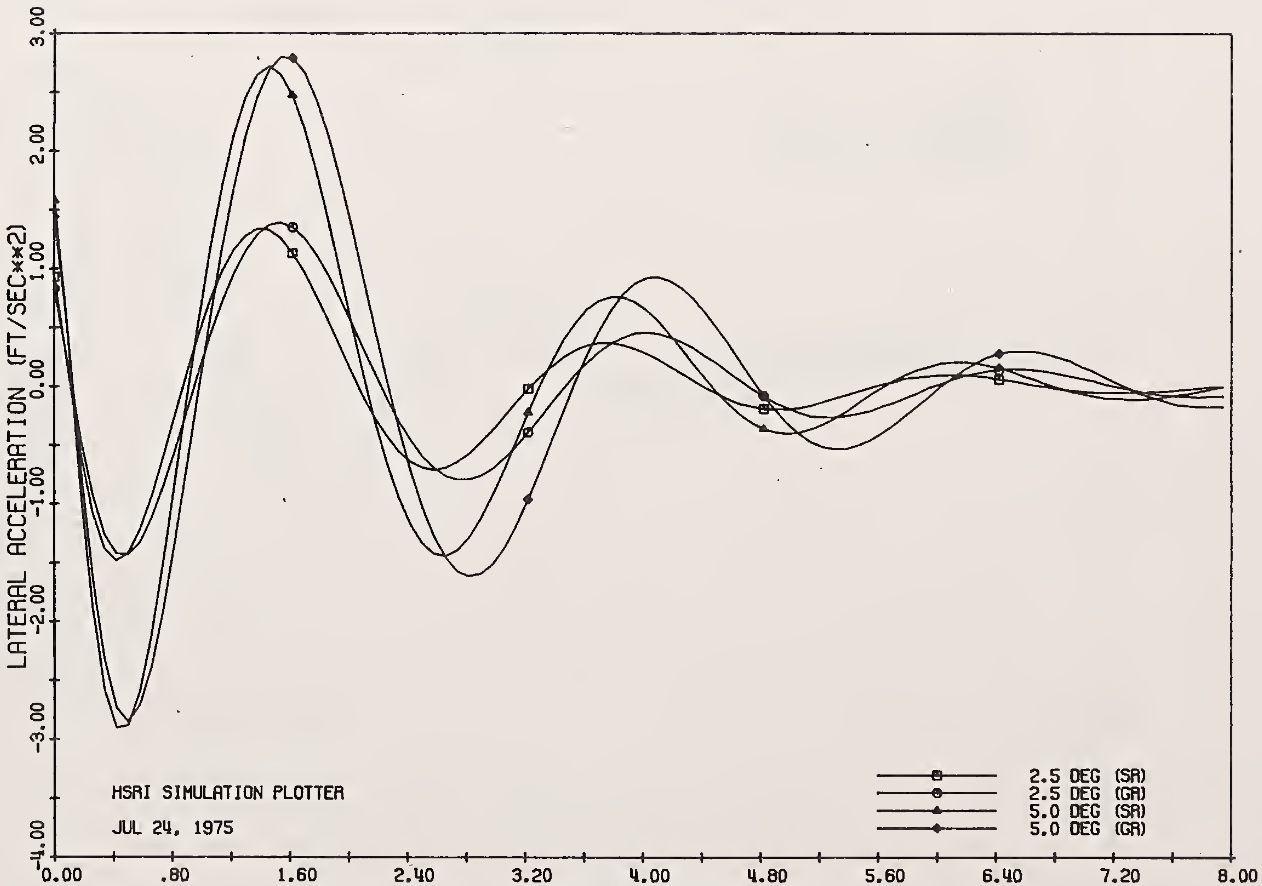

FIGURE 21 MUSTANG-TRAILER, 30 MPH, GAMMA (O) VARIED, SMOOTH OR GROOVED ROAD (SR OR GR)

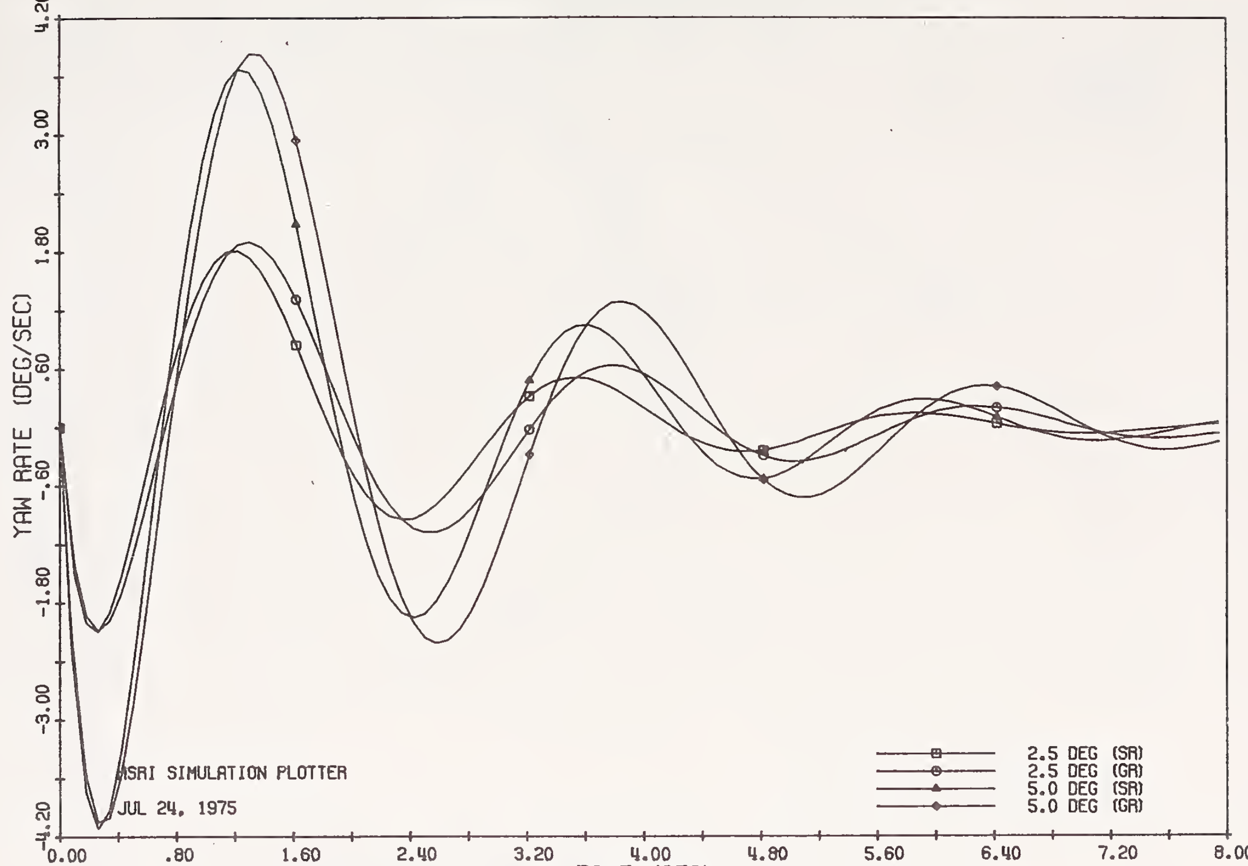

FIGURE 22 MUSTANG-TRAILER, 30 MPH, GAMMA (0) VARIED, SMOOTH OR GROOVED ROAD (SR OR GR)

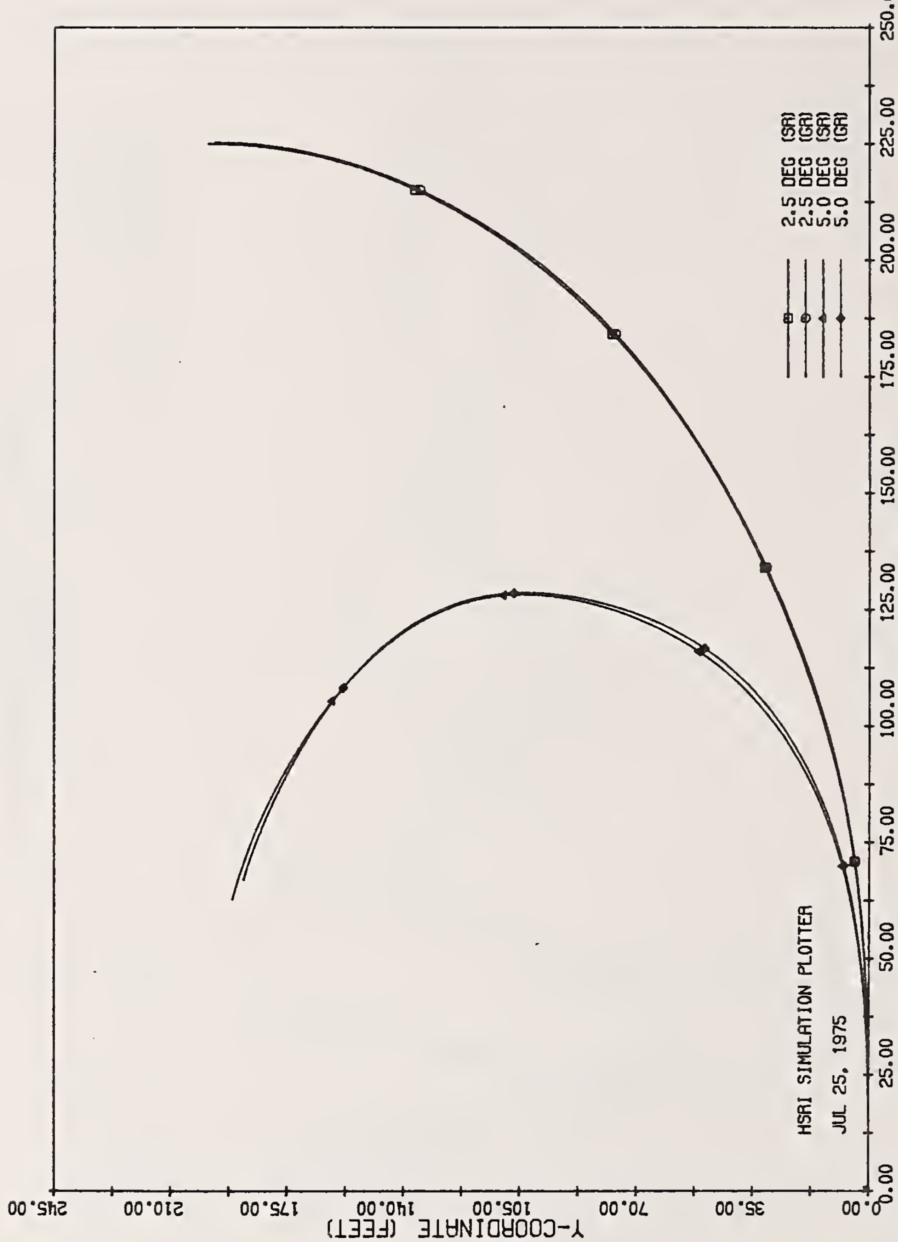

FIGURE 23 MUSTANG-TRAILER,30 MPH,DELTA VARIED,SMOOTH OR GROOVED ROAD(SR OR GR)

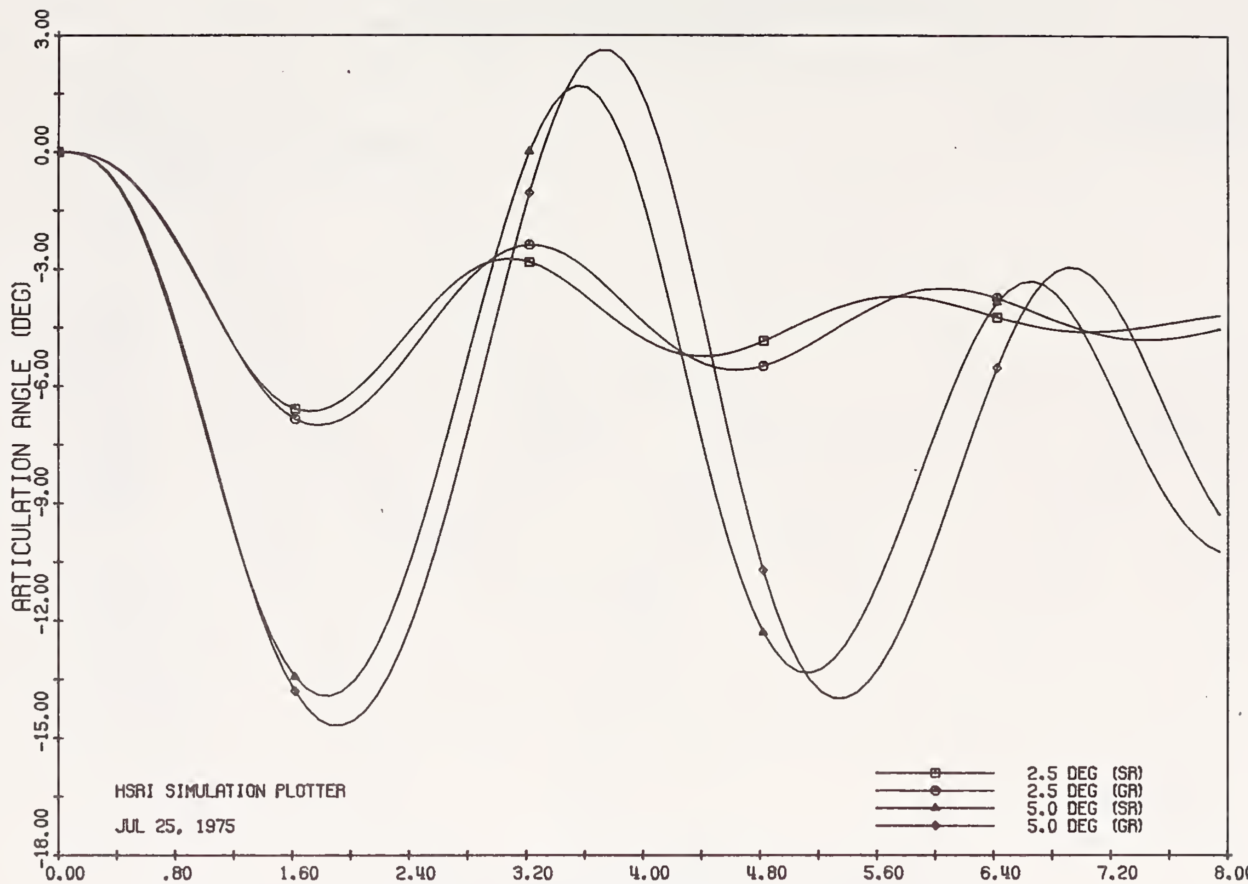

FIGURE 24 MUSTANG-TRAILER, 30 MPH, DELTA VARIED, SMOOTH OR GROOVED ROAD (SR OR GR)

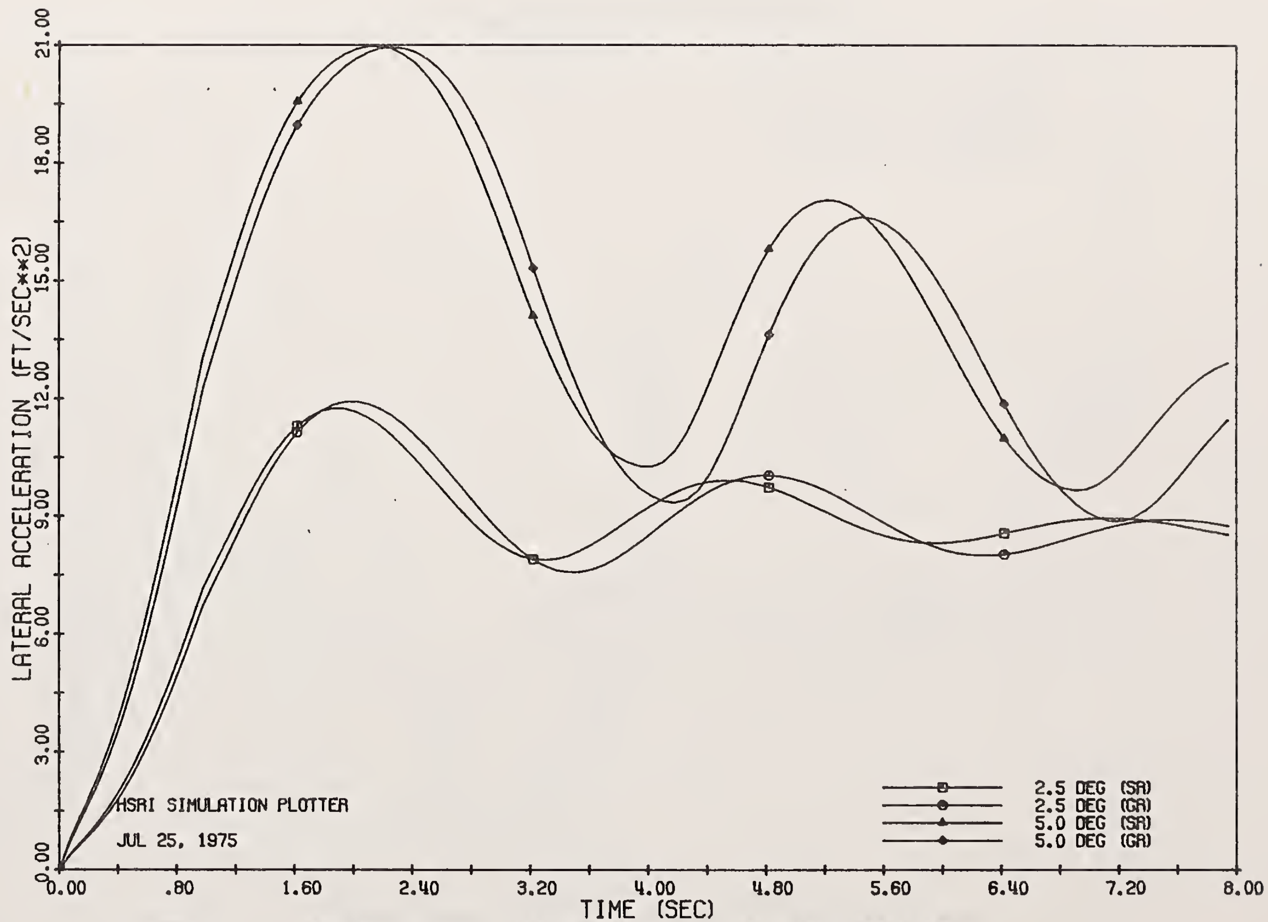

FIGURE 25 MUSTANG-TRAILER, 30 MPH, DELTA VARIED, SMOOTH OR GROOVED ROAD (SR OR GR)

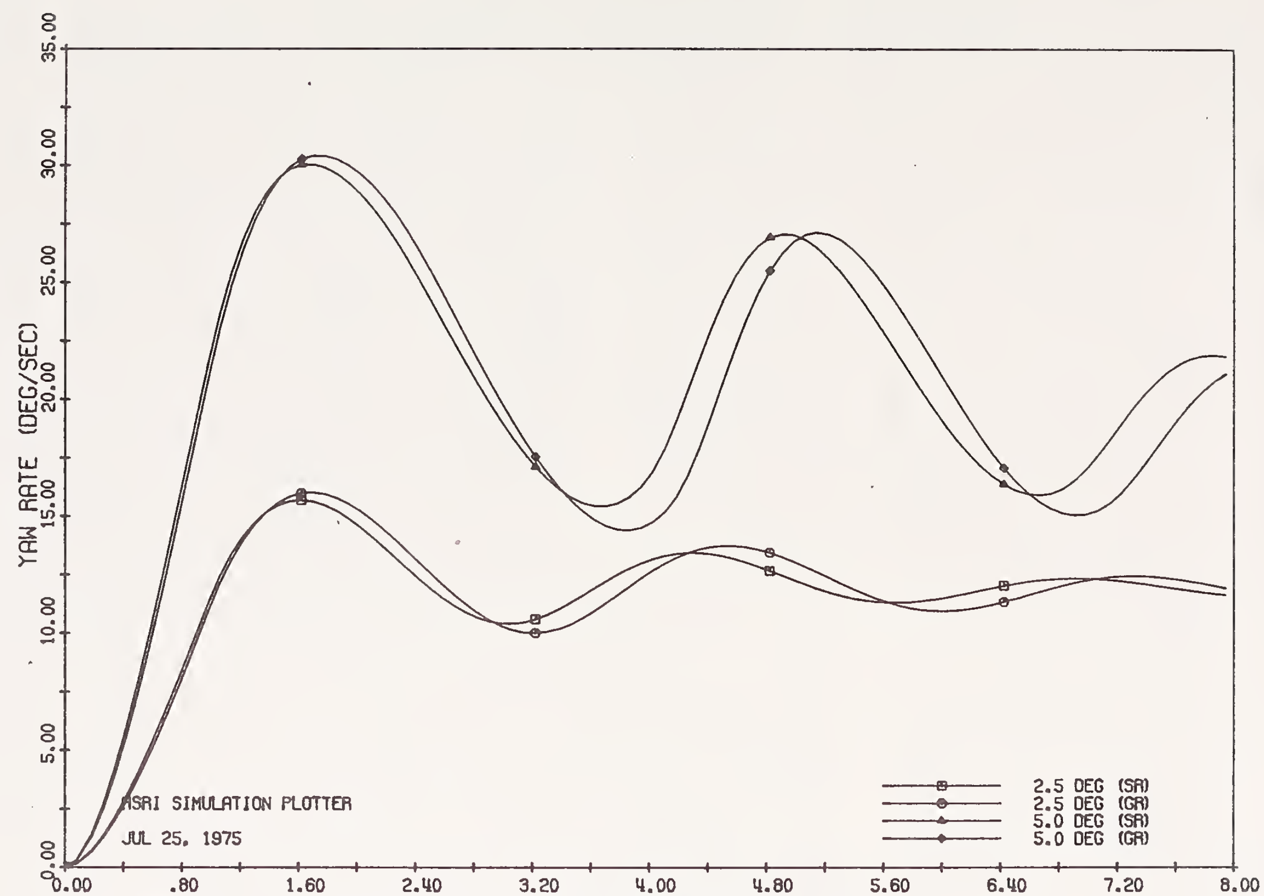

FIGURE 26 MUSTANG-TRAILER, 30 MPH, DELTA VARIED, SMOOTH OR GROOVED ROAD (SR OR GR)

The lane change maneuvers are presented in Figures 27-30. The steer input was a sine wave of 2.5^{0} amplitude and a two-second period. After two seconds, the simulated steer angle remained zero. As in the previous two cases, there is not much difference between smooth road and grooved road results.

There are twelve computer runs presented in Figures 19-30. Based upon the representations of the smooth and grooved tire/road interface, the smooth and grooved road results do not differ significantly.

Now consider the straight-line braking results. These results were obtained using the HSRI braking model, BRAKES2. This single degree of freedom model is described in Reference 15. The maximum unlocked deceleration of the wheels is calculated based on the peak coefficient of friction.

The vehicle and tire data are given in Tables 5 and 6. The results are plotted in Figure 31. Based upon the regression model, better performance is predicted on grooved pavement than on smooth pavement for low μ, whereas better performance on smooth pavement rather than grooved pavement is predicted for high μ.

The results of the motorcycle study presented in Appendix F are rather inconclusive. The simulated maneuver was the traversal of a section of grooved pavement by a motorcycle following the line of the roadway. Steering torque data were obtained in full-scale tests by means of a torque sensor located between the handlebars and front fork of the test motorcycle. This experimentally recorded torque signal was then digitized and used as a disturbance input to the motorcycle computer simulation. The steer angle was also recorded so that it could be used later for comparison purposes. The front and rear side forces resulting from the disturbance were modified by using the grooving function described in Chapter III.

The only parameter available for comparing simulated and experimental results was the steer angle, hence no firm conclusions were reached as to how well this method of simulating grooved pavement response on the computer compares with full-scale test results. The agreement between

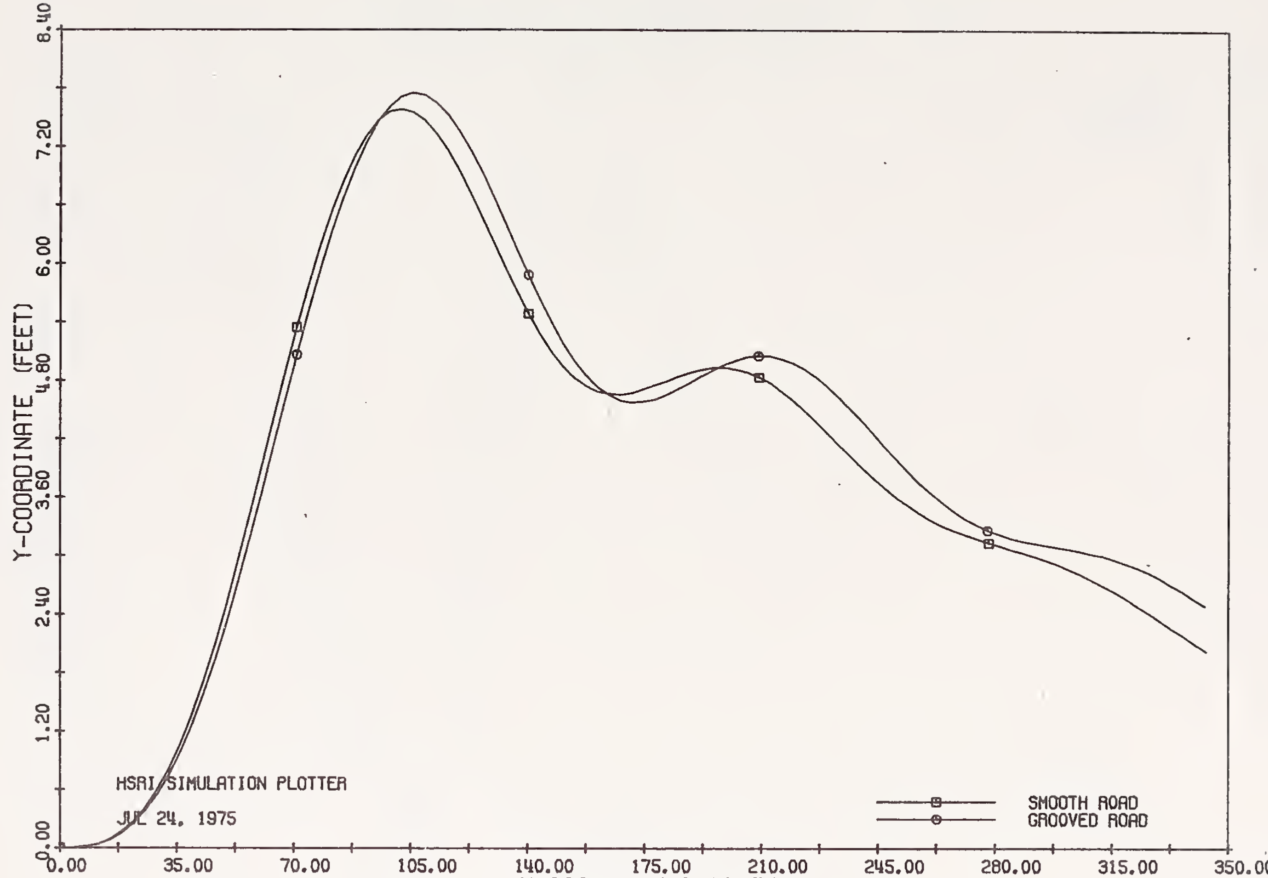

FIGURE 27 MUSTANG-TRAILER, 30 MPH, SINUSOIDAL STEER WITH AMP = 2.5 DEG

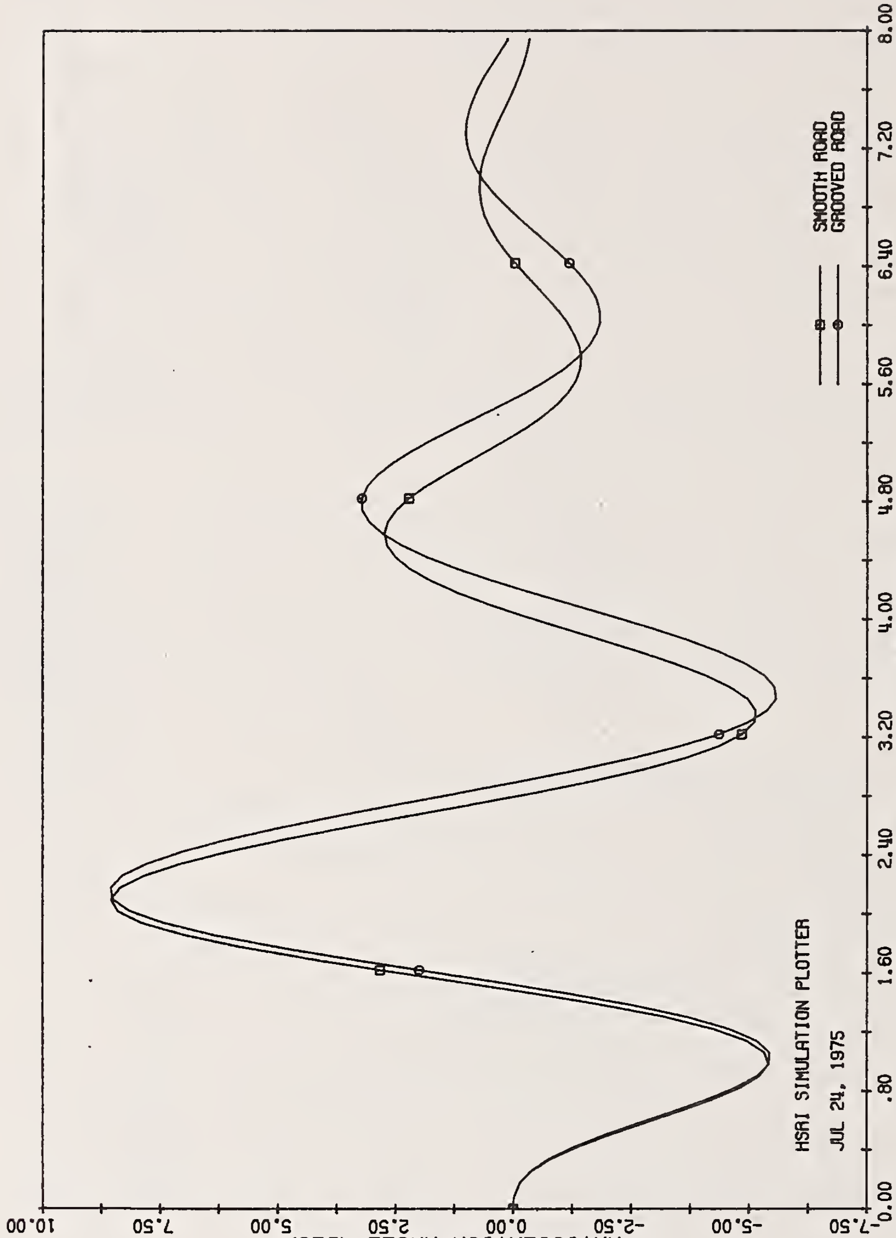

FIGURE 28 MUSTANG-TRAILER, 30 MPH, SINUSOIDAL STEER WITH AMP = 2.5 DEG

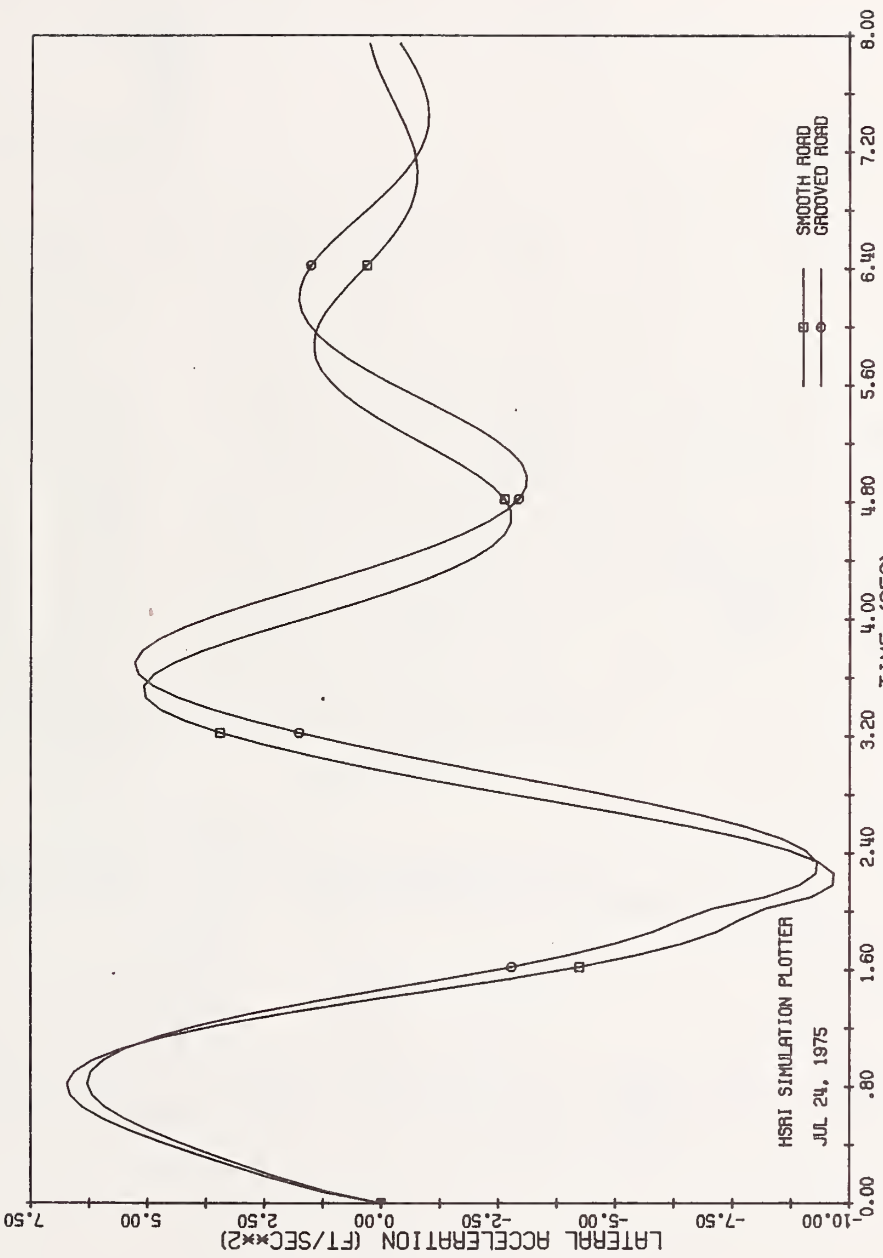

FIGURE 29 MUSTANG-TRAILER, 30 MPH, SINUSOIDAL STEER WITH AMP = 2.5 DEG

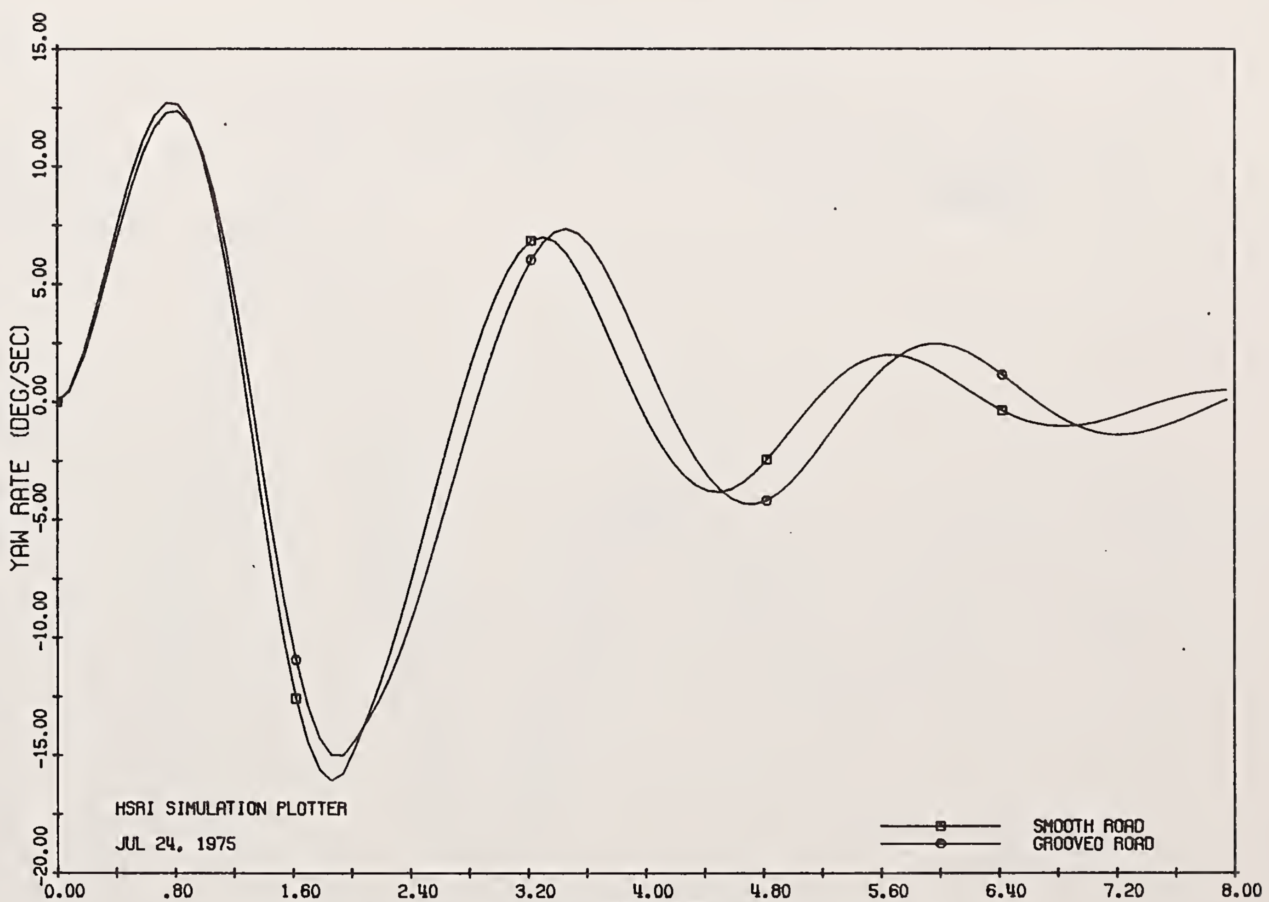

FIGURE 30 MUSTANG-TRAILER, 30 MPH, SINUSOIDAL STEER WITH AMP = 2.5 DEG

TABLE 5: VEHICLE DATA AND RESULTS OF AUTOMOBILE-TRAILER SIMULATION IN BRAKING

ENTER DATA

01	A1	DISTANCE BETWEEN TRACTOR C.G. AND TRACTOR FRONT SUSPENSION (IN)	48.3
02	A3	DISTANCE BETWEEN TRAILER C.G. AND FIFTH WHEEL (IN)	108.2
03	A4	DISTANCE BETWEEN TRAILER SUSPENSION AND TRAILER C.G. (IN)	17.8
04	BB	DISTANCE BETWEEN FIFTH WHEEL AND TRACTOR REAR SUSPENSION (IN). (FIFTH WHEEL LOCATED AFT OF SUSPENSION IS POSITIVE)	36.0
05	L	WHEELBASE OF TRACTOR (IN)	109.
06	H	HEIGHT OF TRACTOR C.G. ABOVE GROUND (IN)	20.4
07	HH	HEIGHT OF FIFTH WHEEL ABOVE GROUND (IN)	17.1
08	HT	HEIGHT OF TRAILER C.G. ABOVE GROUND (IN)	36.1
09	GVW1	WEIGHT OF TRACTOR (LB)	3660.0
10	GVW2	WEIGHT OF TRAILER (LB)	2106.0

DO YOU WISH TO INPUT BRAKE DISTRIBUTION (23) ? Y

TIRE PARAMETERS

ROLLING RADIUS OF TIRE (IN), PEAK FRICTION COEFFICIENT,
EFFECTIVE (OR SLIDING) FRICTION COEFFICIENT: R, MUP, MUE

```
AXLE 1  (14, 17, 20)     12.7, .59, .05
AXLE 2  (15, 18, 21)     12.7, .59, .05
AXLE 3  (16, 19, 22)     12.5, .59, .05
23 ENTER BRAKE RATIO:    6.48, 4.344, 0.
PEAK DECEL OR FIRST AXLE TO LOCK OR CYCLE (P OR F)? F
```

END DATA INPUT

TABLE 5: (CONTINUED)

THE DECEL OBTAINED WITH BRAKE TORQUE RATIO OF 6.48 : 4.34 : 0.00
JUST PRIOR TO LOCKUP (CYCLING) IS APPROXIMATELY 12.6 FPSPS.

	AXLE 1	AXLE 2	AXLE 3
TOTAL ATTEMPTED TORQUE PER AXLE (IN-LB):	17172.77	11512.12	0.00
STATIC LOADING (LB):	1939.92	2017.59	1808.49
DYNAMIC LOADING (LB):	2296.57	1785.38	1684.05
BRAKE FORCE (LB):	1352.19	906.47	0.00
EFFECTIVE FRICTION (FX/FZ):	0.59	0.51	0.00
HITCH FORCES (LB) STATIC:	FX= 0.00	FZ= 297.51	
(COMPRESSION POS.) DYNAMIC:	FX=824.83	FZ= 421.95	

AXLE 1 JUST PRIOR TO LOCKING (CYCLING).

INITIAL VELOCITY (MPH): 30.0
BRAKE DELAY TIME (SEC): .25
THE ESTIMATED STOPPING DISTANCE IS 88. FEET.

TABLE 6

DATA FOR TTI REGRESSION MODEL FOR BRAKES2 SIMULATION

X_4	1100 (front), 890 (rear)
X_6	.11
X_7	.125
X_{10}	.89, .567
X_{12}	30
X_{13}	40
X_{15}	.98, .59
X_{16}	.127

Exponent of:

e	.0207
X_4	-.01781
X_6	-.20436
X_7	-.02343
X_{10}	.33188
X_{11}	.97932
X_{12}	.0620
X_{13}	-.04288
X_{15}	-.77221
X_{16}	.20619

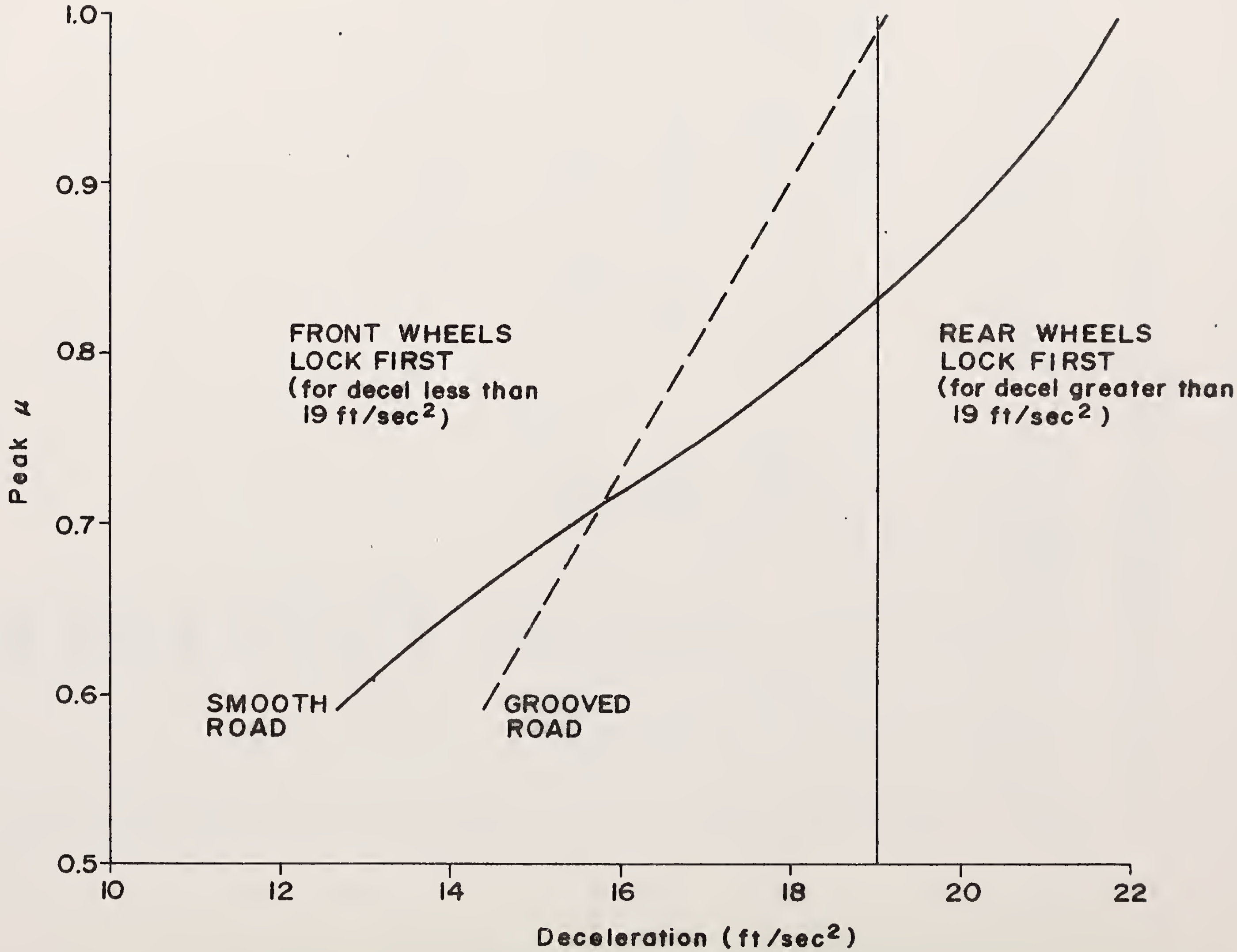

FIGURE 31 - PEAK μ vs. DECELERATION for MUSTANG-TRAILER.

simulated and experimental steer responses for the simulation runs was not particularly good. No actual oscillations of the motorcycle that could be termed weave or wobble were noted, either in the simulated or experimental steering time histories.

One conclusion that can be reached concerns the effect of the grooving function on the motorcycle response. Since comparison of the plotted results shows virtually the same trends, the indication is that pavement grooving has very little effect on motorcycle response under the conditions studied.

Several computer runs were made with the HVOSM computer program. The runs considered different pavements (SN = 75 and SN = 25) and constant steer maneuvers for a medium weight vehicle traveling on a 400 ft radius curve at 50 MPH. The run made on the high friction pavement showed a very slight increase in lateral force due to the grooving, whereas the results of the low friction pavement run indicate a significantly beneficial effect due to grooving. The latter results are plotted in Figures 32-36 and show that the vehicle is considerably more stable for the grooved case than for the ungrooved. The vehicle attains its maximum available lateral force on all four tires during the four second maneuver for the ungrooved condition whereas only the front two tires saturate during the grooved run. Figures 32 and 36 indicate that the grooves provide vehicle directional control as evidenced by the small lateral velocity component. Figure 33 shows that the lateral acceleration on grooved pavements remains dependent on steer input whereas for the ungrooved case the lateral acceleration has become independent of steering input. Figure 34 indicates that the oscillations in sprung mass yaw rates for the grooved case seem to decay to a steady state value; those for the ungrooved case diverge rapidly after two seconds. Figure 35 reveals that the vehicular yaw angle for the ungrooved case is larger than that of the grooved case and continues to increase throughout the simulation. From these runs it appears that the beneficial effects of pavement grooving are greater for the lower friction pavements. However, the results at the low skid number represent an extrapolation of measured data.

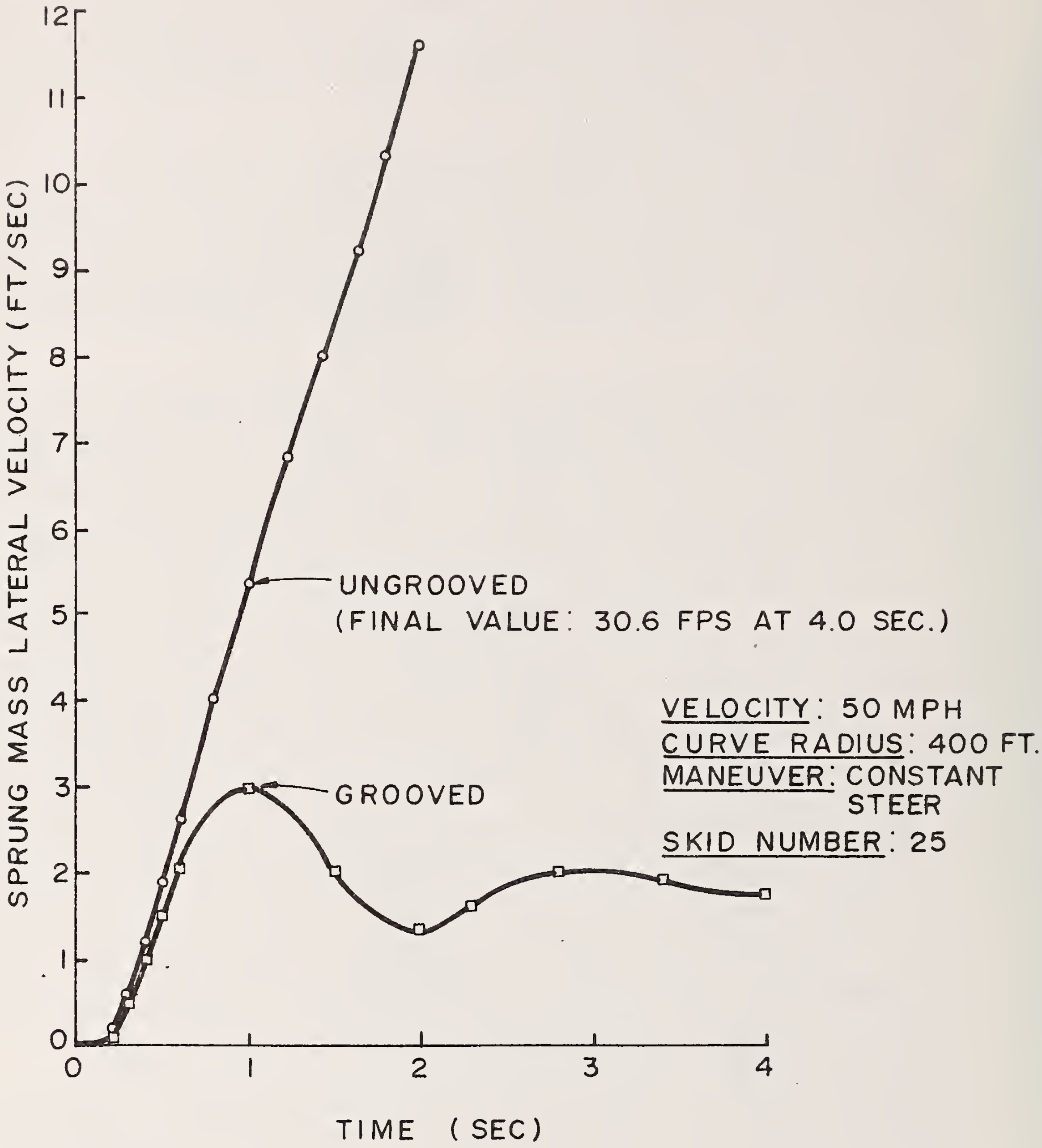

FIGURE 32: HVOSM COMPUTER SIMULATION LATERAL VELOCITY RESULTS.

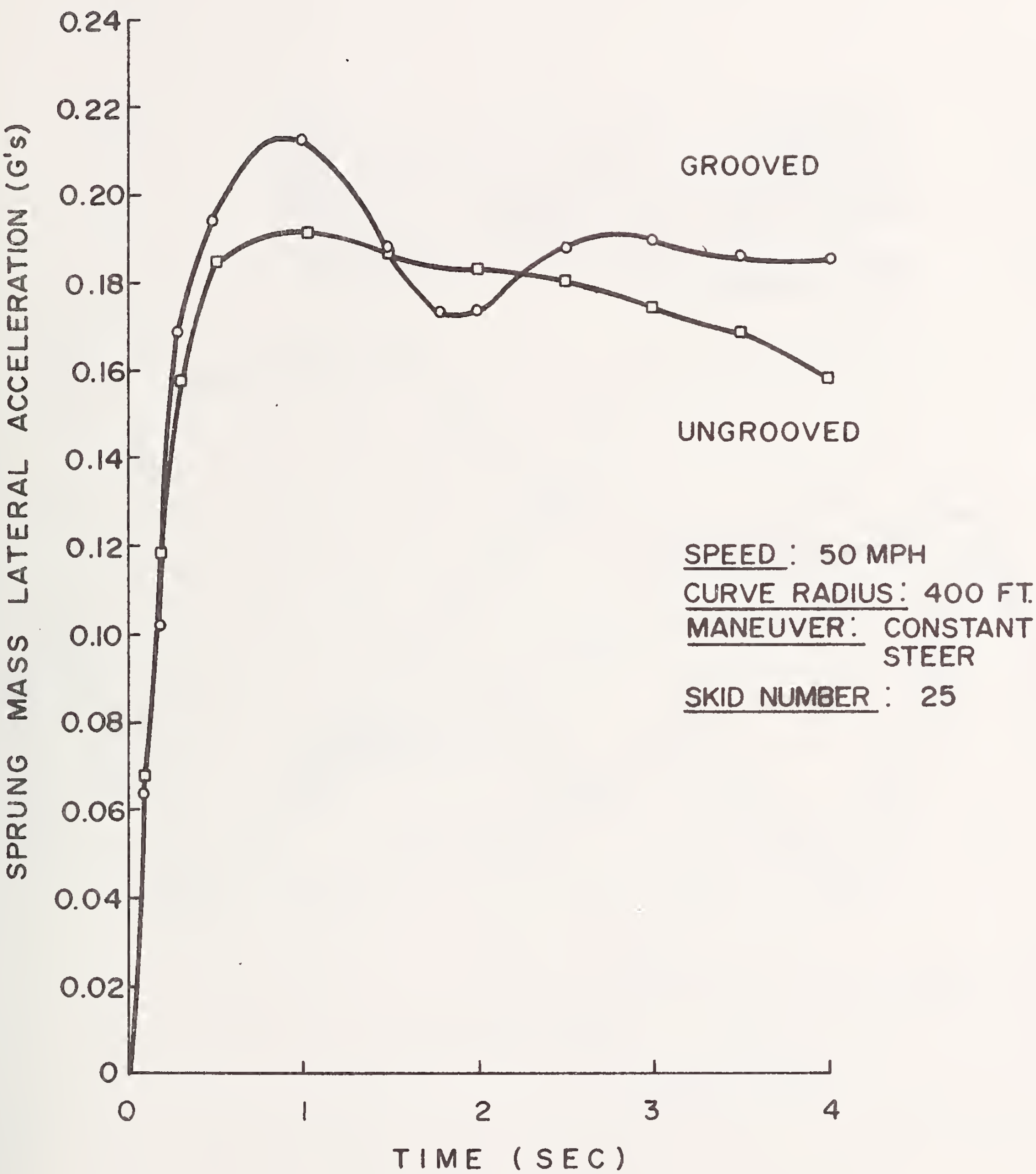

FIGURE 33: HVOSM COMPUTER SIMULATION LATERAL ACCELERATION RESULTS.

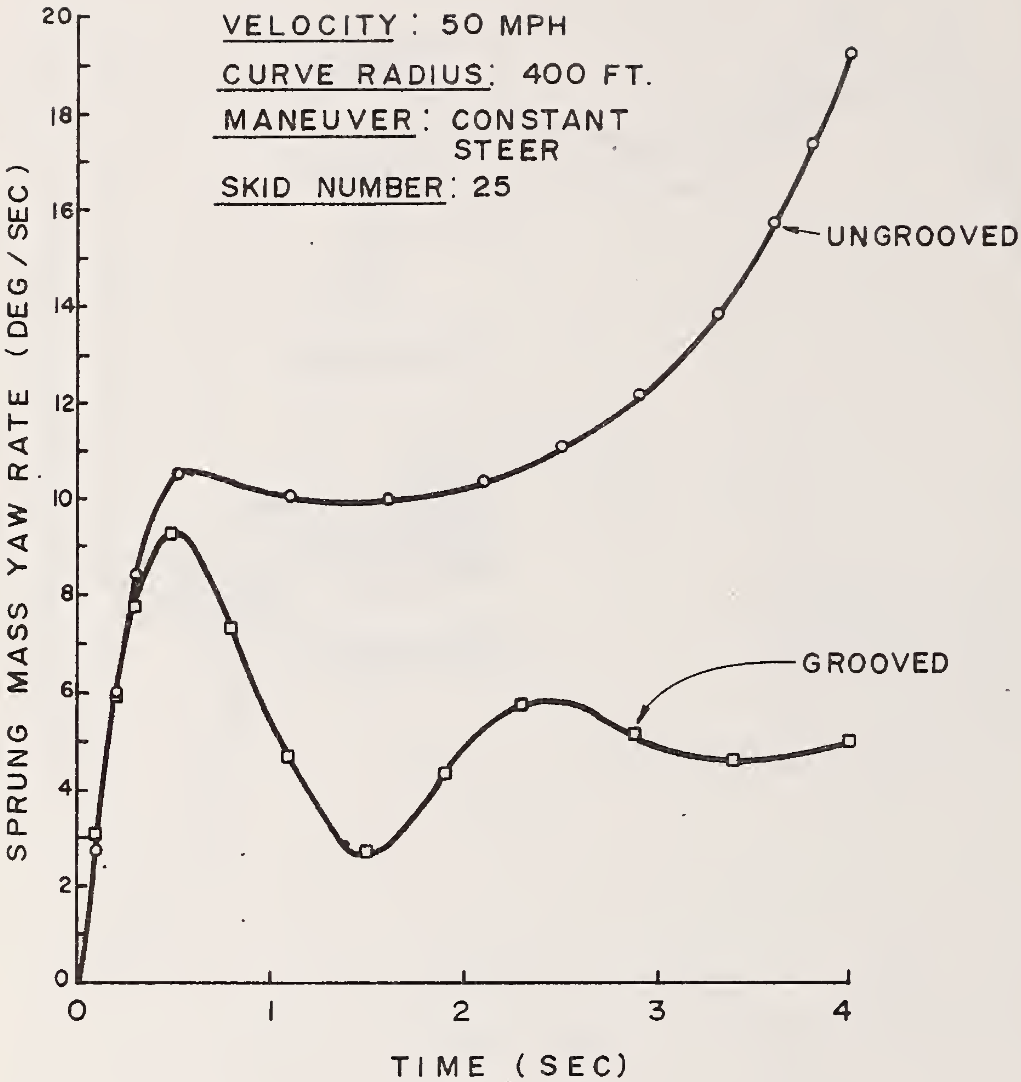

FIGURE 34 - HVOSM COMPUTER SIMULATION YAW RATE RESULTS.

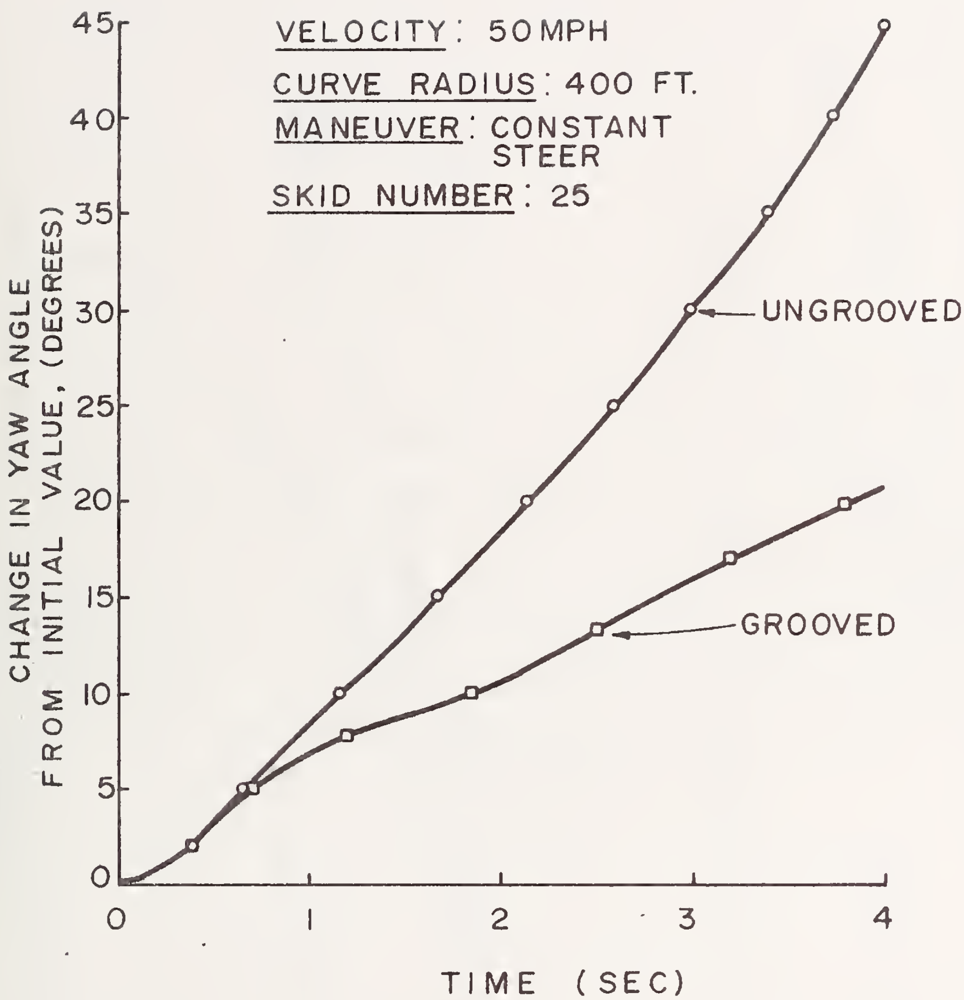

FIGURE 35 - HVOSM COMPUTER SIMULATION YAW ANGLE RESULTS.

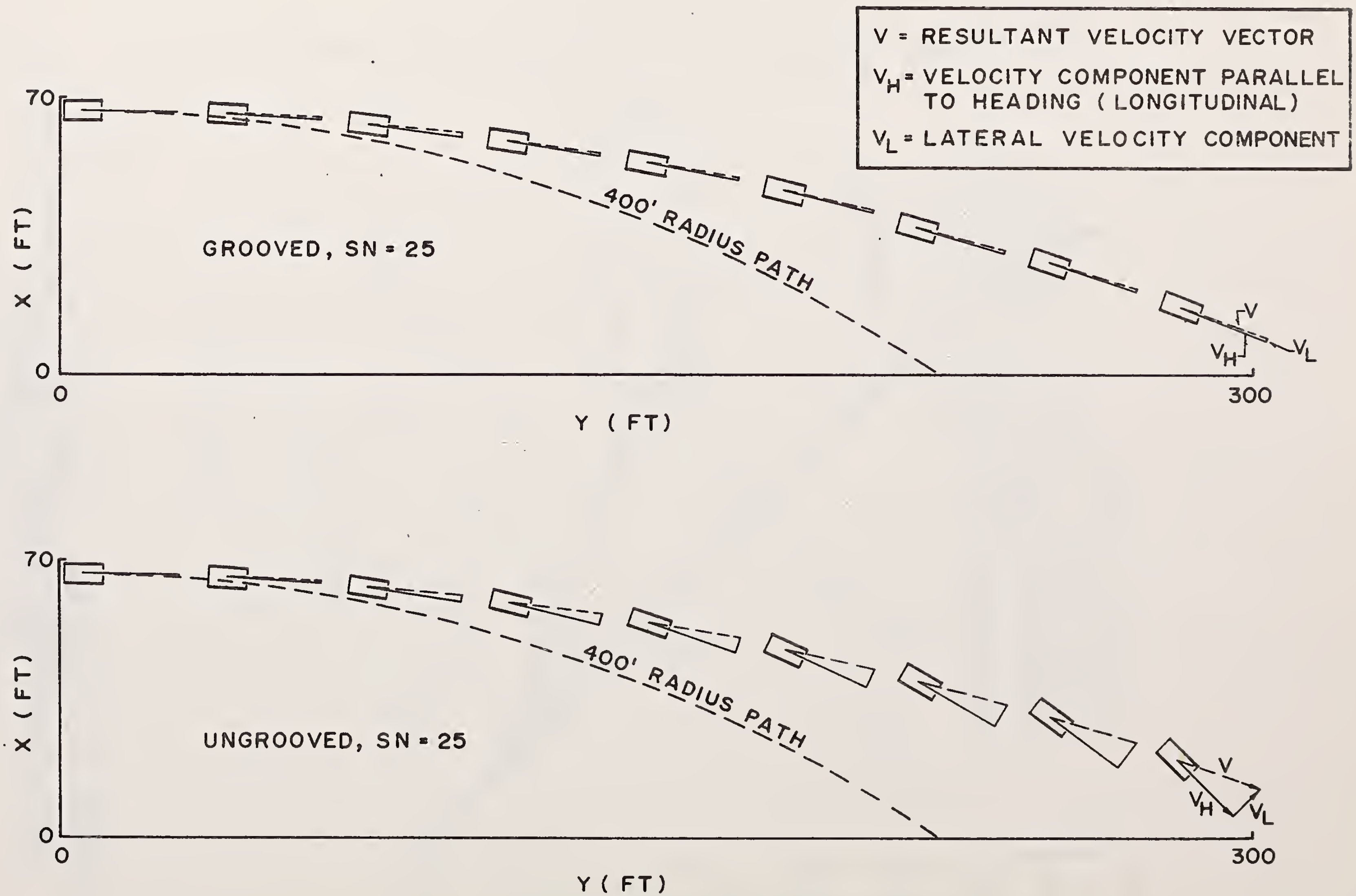

FIGURE 36: HVOSM RESULTS FOR CONSTANT STEER MANEUVER AT 50 MPH ON LOW-FRICTION PAVEMENT.

Table 7 presents a statistical comparison of the experiments conducted on groove geometry. Chapter I provides a background for the comparison. Experiments were designed to evaluate the differences, if any, between groove spacing, depth, width, and orientation. A boat trailer tire was employed along with slip angles of 4^{0}, 8^{0}, 16^{0}, camber angles of 0^{0} and approach angles of 0^{0}, 10^{0}, and -10^{0}. The pavement surfaces considered both wet and dry PCC.

A paired "t" test comparing the data was used. The same slip and camber angles were employed and only variations in groove geometry were allowed. The object of the pairing of the samples was to increase the precision of comparison between the sample pavements and insure against possible shifts in side force values due to inherent property changes of the tire. The results presented in Table 7 reveal that, in general, a variation in groove geometry has little effect on the measured side forces. The only evident difference involved approach angles of $+10^{0}$ and -10^{0}, on wet pavements (Experiment 4). For this case, the .110" x 1/8" x 1" surface produced higher measured side force than the .220" x 3/8" x 1½" surfaces. It should be emphasized that these tests were based upon a limited amount of free-rolling data taken at a constant vehicle speed; thus, they should be interpreted with caution.

TABLE 7 STATISTICAL COMPARISON OF GROOVE GEOMETRY

Exp. No.	Slip Angle (DEG)	Camber Angle (DEG)	Approach Angle (DEG)	Load (LBS)	Pavement	Groove Geometry	Comment
1	4,8,16	0,5,10	0	400	dry PCC	.110 x 1/8 x 1	Comparison between groove geometries is not significant
	4,8,16	0,5,10	0	400	dry PCC	.220 x ¼ x 1½	
2	4,8,16	0,5,10	+10	400	dry PCC	.110 x 1/8 x 1	Comparison is not significant
	4,8,16	0,5,10	-10	400	dry PCC	.220 x 3/8 x 1½	
3	4,8,16	0,5,10	0	400	wet PCC	.110 x 1/8 x 1	Comparison is not significant
	4,8,16	0,5,10	0	400	wet PCC	.220 x ¼ x 1½	
4	4,8,16	0,5,10	+10	400	wet PCC	.110 x 1/8 x 1	Comparison is significant
	4,8,16	0,5,10	-10	400	wet PCC	.220 x 3/8 x 1½	
5	4,8,16	0,5,10	0	400	dry PCC	.110 x 1/8 x 1	Comparison is not significant
	4,8,16	0,5,10	0	400	dry PCC	.220 x ¼ x 1½	
6	4,8,16	0,5,10	0	400	dry PCC	.220 x ¼ x 1½	Comparison is not significant
	4,8,16	0,5,10	-10	400	dry PCC	.220 x 3/8 x 1½	
7	4,8,16	0,5,10	0	400	dry PCC	.110 x 1/8 x 1	Comparison is not significant
	4,8,16	0,5,10	-10	400	dry PCC	.220 x 3/8 x 1½	
8	4,8,16	0,5,10	+10	400	dry PCC	.110 x 1/8 x 1	Comparison is not significant
	4,8,16	0,5,10	-10	400	dry PCC	.220 x 3/8 x 1½	
9	4,8,16	0,5,10	0	400	wet PCC	.110 x 1/8 x 1	Comparison is not significant
	4,8,16	0,5,10	+10	400	wet PCC	.110 x 1/8 x 1	
10	4,8,16	0,5,10	0	400	wet PCC	.220 x ¼ x 1½	Comparison is not significant
	4,8,16	0,5,10	-10	400	wet PCC	.220 x 3/8 x 1½	
11	4,8,16	0,5,10	0	400	wet PCC	.110 x 1/8 x 1	Comparison is not significant
	4,8,16	0,5,10	-10	400	wet PCC	.220 x 3/8 x 1½	
12	4,8,16	0,5,10	+10	400	wet PCC	.110 x 1/8 x 1	Comparison is not significant
	4,8,16	0,5,10	-10	400	wet PCC	.220 x ¼ x 1½	

CHAPTER VI
CONCLUSIONS

The beneficial effects of pavement grooving include their ability to drain pavements, provide directional stability and reduce the number of accidents during wet-weather periods. These benefits have been pointed out in the literature. In contrast to this, the disconcerting feeling reported by some motorcyclists riding on grooved pavements has been a cause of concern. Although every effort was made, the present study was unable to quantify any detrimental effects of conventional pavement grooving on motorcycle response by objective experimental methods. The "disconcerting feeling" is apparently a very subtle physical condition to detect, requiring the extremely sensitive sensory system of a human being. In this work, the human (motorcycle rider) could detect, in certain high-speed situations, an apparent insecure feeling due to the presence of the grooved pavement. Based upon the testing, theoretical hypotheses, and riding experiments, the phenomenon appears to be one of the tire-groove interaction exciting certain resonant frequencies in motorcycles; the effect is so subtle as to be almost undetectable except in extreme cases of very high speeds or very poorly damped motorcycles.

The results of the articulated vehicle handling studies performed by means of the HSRI computer simulation, in general, did not show much difference between smooth road and grooved road results. The braking results obtained in the same study revealed that slightly higher available friction is predicted on grooved pavement than on smooth pavement for low friction pavements; whereas higher friction on smooth pavement rather than grooved pavement is predicted for high friction pavements. The full-scale testing of the instrumented automobile-trailer combination discussed in Chapter II revealed that the effects of the grooving could not be detected by means of the instrumentation employed.

The study showed, in the range of groove geometries tested, variations in the groove dimensions and approach angle do not produce a significant difference between grooved and ungrooved forces. This is evidenced by the exponent of these geometric variables in the grooving power laws.

A list of specific conclusions drawn from the research will now be presented.

A. Motorcycle

Based upon rider evaluation,

1. The presence of traffic worn grooves is not as evident on motorcycle response as the presence of unworn or newly cut grooves.
2. At speeds up to the legal speed limit of 55 mph no detrimental effect due to conventional groove patterns was found.
3. At speeds approaching 70 mph a perceptible wobble (side to side front wheel movement) is experienced when the rider does not attempt to follow the grooves; only a slight wobble is felt when attempting to follow the grooves.
4. The effect of the grooves does not immediately manifest itself and was more evident when the testing was performed over a ½ mile length of pavement.
5. The effect of a steering damper on the motorcycle's response to the grooves could not be clearly detected (Yamaha RD 350).
6. The effect of the grooves on motorcycle response is more noticeable for knobby tires than for factory equipped street tires.
7. Riding over transverse grooves (perpendicular to approach direction) does not produce undesirable effects.
8. Lowering the tire inflation pressure by 10 psi from the recommended value does not affect the motorcycle's grooving response.
9. For similar conditions, a steel tine longitudinally textured pavement produces a more noticeable motorcycle disturbance than the grooved pavements tested.
10. For the grooving configurations considered and the test motorcycle employed, pavement grooving cannot be considered hazardous for speeds up to 70 mph except perhaps to the most inexperienced rider.

Based upon the electronic instrumentation and computer simulation employed,

11. The effects of pavement grooving could not be detected.
12. The grooving power law predicts very little difference on motorcycle response between grooved and smooth pavements under the conditions used in the study.
13. No actual oscillations of the motorcycle that could be termed weave or wobble were noted, either in the simulated or experimental steering time histories.

B. Automobile-trailer Combination

Based upon instrumented full-scale testing,

1. The effects of the grooving could not be detected at different speeds for various trailer and tongue loads when a typical small car-towed vehicle combination was tested.

Based upon driver evaluation,

2. At a speed of 50 mph the driver of the small car-towed vehicle combination experienced a slight vibration in the steering wheel even though the system remained extremely stable.

Based upon full-scale testing and driver evaluation,

3. The effects of pavement grooving are not detrimental to a small car-towed vehicle combination.

Based upon computer simulation that employs the grooving function resulting from single-tire test data,

4. There is no significant difference between smooth road and grooved road response for the cornering maneuvers described in Chapter V.

C. Automobile

Since there was no instrumented full-scale vehicle testing, the following conclusions for the automobile are based upon computer simulation with the HVOSM computer program. These conclusions are:

1. For cases involving braking (see Chapter IV), the higher speeds show the effects of grooving are quite beneficial. However, it should be emphasized that data were only collected at the higher skid numbers (60 and above) and the curves shown in Figure 18 are based upon the single tire model.

2. From free-rolling studies, the effect of grooving is more beneficial for the lower friction pavements (Figure 13).
3. From free-rolling studies, the effect of grooving approach angle (angle between wheel velocity vector and the grooves) is minor.
4. Also from free-rolling studies, the grooving model predicts larger grooved than smooth side forces for the speeds, slip angles, and skid numbers considered.
5. The HVOSM computer model predicts a slight beneficial effect due to the grooves for a constant steer maneuver at 50 mph on a 400 ft. radius curve and a high friction pavement (SN = 75).
6. The HVOSM computer model predicts a very significant beneficial effect due to the grooves for a turning maneuver at 50 mph on a 400 ft. radius curve and a low friction pavement (SN = 25).

In conclusion, it should be emphasized that a valid grooving function to predict motorcycle and automobile response has been developed. The modifications made to the handling programs have been made in a very general manner so it would be a routine matter to change the grooving function to reflect the inclusion of more data.

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13. Bernard, James E., et al, "A Computer Based Mathematical Method for Predicting the Directional Response of Trucks and Tractor-Trailers", Technical Report UM-HSRI-PF-73-1, Highway Safety Research Institute, University of Michigan, Ann Arbor, Michigan, June 1973.

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APPENDIX A

ANNOTATED LITERATURE SURVEY OF PAVEMENT GROOVING

1. Zube E, Skog JB, Kemp GR. FIELD AND LABORATORY STUDIES ON SKID RESISTANCE OF PAVEMENT SURFACES. California Division Highways, Bureau of Public Roads /US/HPR-1 (5), B-3-1.

One of the most important properties of a pavement surface is its skid resistance characteristics. A wet weather accident analysis involving California highways indicates that most of the single car accidents occur on curves. The average friction value as determined by the California skid tester for this analysis was 0.22F. However, twenty-eight percent of the accidents that occurred on curves were in the 0.25F-0.28F range. Cross correlation with the British portable tester places all results for minimum remedial action values from England, Virginia, Florida and California in the range of 0.25F-0.30F, as measured under California test conditions. A rather comprehensive study has been completed on the improving of the skid resistance of PCC pavements by serration. The type of grooving pattern used influences the reaction of people driving motorcycles or light cars over longitudinal (parallel to the centerline) serrations. It appears that the nature of the existing concrete surface and the type of serration pattern influence the degree of improvement in friction values. A marked reduction in wet weather accidents has occurred in critical curve areas that have been serrated. A detailed analysis of 170 single vehicle accidents that occurred during rainy weather in 1964 indicated that 152 or 90 percent of these happened during periods of heavy rainfall where dynamic hydroplaning might have been a possibility. Factors such as excessive speed under extremely poor driving conditions appear to be important in the reported skidding accidents during heavy rainfall. /Author/

2. TOOLS OF THE TRADE. Concrete Construction, vol 14, No. 4, pp 121-125, 1 fig, 13 phot. Apr69.

Tools, powered and directed by hand and used by the concrete craftsman, are reviewed. The design and use of these tools are discussed. The tools include straight edges, tampers, floats, trowers, edgers, groovers, brushes and brooms, percussion tools, rubbing bricks, and rendering tools.

3. Spellman DL. TEXTURING OF CONCRETE PAVEMENT. Highway Research Board Special Reports, No. 101, pp 100-103. 69.

Preliminary work by California on texturing of concrete pavements is described. The problem has resolved into two general areas: securing adequate texture during construction and maintaining texture, as built, by using materials and construction practices that insure durable surface mortar. Various texture patterns were formed into the surface of laboratory-cast slabs using a variety of prototype devices. Skid tests were performed on these slabs. A promising pattern was selected and used on short section of three freeways. Some of the results were disappointing. A uniform texture over a large area could not be achieved because of varying mortar properties. It was also discovered that the pattern selected, when formed too deeply, caused an adverse reaction on some vehicles. Additional work is planned using other texture patterns. Other surface treatments included broadcasting of slag and selected coarse sand particles on the surface while dragging with burlaps, and brooming. Skid tests are being performed on a periodic basis, but it is too soon to draw conclusions regarding the long-term skid resistance as affected by traffic and weather. New curing compounds and so-called surface hardeners were applied to short test sections of freeways in an attempt to improve mortar durability. Laboratory tests previously performed indicated that some improvement could be expected from the use of better curing compounds and hardeners. Again, these test sections have not been in service long enough to form any conclusions regarding their effectiveness. Planned future work includes a continuation of texturing studies, a search for effective surface treatments, a study of field practices that affect surface mortar quality and texture, and additional work on grooving of older pavements to obtain or restore adequate skid resistance.

Specifications will be developed as work progresses to improve character and durability of the surface texture. /Author/

4. Spickelmire LS. CONSTRUCTION OF NONSKID PAVEMENT SURFACES. Highway Research Board Special Reports, No. 101, pp 104-109, 2 tab. 69.

   Construction procedures are reviewed that are used in California for the construction of skid-resistant pavements. Construction practices in use with asphalt-concrete paving, portland cement concrete paving, and grooving existing concrete pavement are reviewed. The construction aspects that can be expected to affect performance of new portland cement concrete pavement surface texture seem to be: (1) nature of the concrete aggregate, (2) amount of mixing water used, (3) nature and amount of any admixtures used, (4) cement factor, (5) nature and amount of surface manipulation in finishing, (6) amount of additional water used during finishing, (7) amount of bleed water mixed into surface mortar, (8) timing of finishing operations, (9) method and depth of texturing, (10) orientation of texture serrations, (11) timing of the curing operation, (12) effectiveness of curing materials, as applied, (13) extent of curing period before pavement is opened to traffic, (14) amount of abuse by construction equipment in constructing appurtenant facilities, and (15) extent of bump cutting to meet smoothness requirements. The features of grooving that can be expected to affect skid resistance are: (1) width and depth of grooves, (2) spacing of grooves, (3) amount of lane width grooves, (4) orientation. Spreading and compacting asphalt-concrete pavement in California appear to have a very minor effect on the resulting skid resistance. Aggregates available in California for asphalt-concrete mixes are relatively polish resistant. However, experience indicates that surface treatments sometimes lead to loss of skid-resistance value.

5. Gingell VR. GROOVING THE RUNWAY AT WASHINGTON NATIONAL AIRPORT. Civil Engineering ASCE, vol 39, No. 1, pp 31-33, 1 fig, 3 phot. Jan69.

   The Federal Aviation Administration made the decision to groove the main north/south runway at Washington National Airport to preclude the possiblity of high-speed jet aircraft hydroplaning on wet surfaces while landing. Grooves cut into the runway should help drain the surface quickly by preventing ponding and allowing the water to escape from beneath tires, assuring pavement contact. Based on previous tests made under wet and dry conditions on the runway, the friction coefficient varied from 0.25 to 0.75 because of rubber deposits in the touchdown zone and bleeding of asphalt to the surface. After grooving, the friction test showed a constant friction coefficient over the entire surface of 0.70 to 0.75. A much more even braking surface is now provided, and the possibility of hydroplaning is eliminated.

6. Beaton JL, Zube F, Skog J. REDUCTION OF ACCIDENTS BY PAVEMENT GROOVING. Highway Research Board Special Reports No. 101, pp 110-125, 5 fig, 4 tab, 6 ref, 1 app. 69.

    Providing and maintaining a skid-resistant surface on concrete pavement is discussed. Studies of the effect of grooving the pavement to reduce wet weather accidents were conducted. The objective of the studies was to determine the efficiency of serrations in raising the skid resistance, to determine resistance of a grooved pavement to wear and polish of traffic, and to determine the extent of reduction in wet weather accidents by serration of the pavement. Results show that pavement grooving parallel to the centerline will reduce the wet weather accident rate in low friction value areas of PCC pavements. Friction value is raised following grooving. Wear and polish of grooved areas appear to depend on characteristics of the pavement. /Author/

7. Slama R. SLIPPERINESS OF RUNWAYS /IN FRENCH/, Revue Gen Des Routes & Aerodr /France/, No. 443, pp 83-91, 8 fig, 5 phot. May69.

    Two aspects of the slipperiness of runways which have come to the fore because of the increase in landing speed are considered: (1) evaluation of slipperiness with a view to correcting aircraft performance as a function of runway conditions, and (2) development of techniques to give runway surfacings high adhesiveness under all weather conditions. New concrete pavements are subjected to transverse grooving when the concrete is still fresh. In the case of existing concrete pavements, transverse grooving is carried out by an abrasive machine. /LCPC/A/RRL/

8. Bonzel J, Walz K. EFFECT OF THE COMPOSITION AND SURFACE TEXTURE ON SKID-RESISTANCE AND WEAR /IN GERMAN/. European Cement Association /France/ vol 2, pp 297-304, 8 tab, 4 phot, 17 ref. Jul67.

   Current investigations into the effect of concrete mix-design and surface texture on the wearing and skidding resistance of concrete pavements are described. Laboratory test results showed the finely grooved concrete surfaces (spacing of grooves: 2.5 mm) have a higher coefficient of friction than smooth surfaces or surfaces with coarse grooves. The influence of the grading and mineralogical characteristics of aggregates on skidding resistance has not been defined yet but, during laboratory wearing tests, the skidding resistance was considerably increased by the addition of hard aggregates in the surfacing course. Further data will be obtained from test cylinders placed in the surfacing of heavily trafficked concrete roads. Attention is drawn to the need for selecting economical and practical methods of improving wearing and skidding resistance of concrete pavements. /LCPC(A) /RRL/

9. Walz K, Bonzel J. THE RELATION BETWEEN SKIDDING RESISTANCE, WEARING PROPERTIES, CONCRETE COMPOSITION, AND THE CONSTRUCTION OF CONCRETE ROADS /IN GERMAN/. Strassen und Tiefbau /Germany/ vol 22, No. 10, pp 761-768, 7 tab, 10 phot, 17 ref. 68.

   In a discussion of the practical connections between slipperiness, wearing properties and concrete composition, particular reference is made to the following points: the use of fine groving (grooves about 2.5 mm apart) results in especially skid-resistant concrete roads; and their durability is increased by the use of quartz sand mortar, low water-cement value, well distributed air voids, and optimum selection and grading of aggregates. /FG/RRF/

10. Kirkham RH, Maynard DP. METHODS FOR IMPROVING THE SKIDDING RESISTANCE OF CONCRETE SURFACES. European Cement Association /France/ vol 2, pp 281-291, 10 fig, 1 tab, 1 phot, 4 ref. Jul69.

Factors affecting the skidding resistance of concrete roads are investigated. Details are given of the accelerated wear machine developed, accelerated wear tests and road trials. Three main topics are discussed: (1) development of rough texture on new surfaces; (2) effect of the concrete mix; and (3) development of rough texture on old surfaces. To produce coarse texture on new concrete, it is recommended to use a broom made of steel tape and to brush the surface transversely to the direction of the traffic. A comparison is made of the efficiency of various types of brooms by measuring wear, sideway force coefficient, and braking force coefficient. To study the influence of the concrete mix, wearing and polishing tests were conducted on concrete and mortar containing aggregates varying in grading and quality. It was found that the addition of fine aggregates with a high resistance to polishing, such as calcined Bauxite, results in an increase in skid resistance. With regard to the grooving of old concrete roads, a diamond pattern and wide grooves at wide spacing seem the most efficient ways of improving skidding resistance. /LCPC/RRL/

11. Leyder JP. SYNTHESIS ON CONCRETE ROUGHNESS /IN FRENCH/. Technique Routiere, Brussels /Belgium/ vol 13, No. 3, pp 1-16, 7 fig, 2 tab, 6 ref. Sep68.

Research on the roughness of a number of experimental sections of road is outlined and findings are given concerning the finishing of rough concrete surfacings and their long term performance. Results of a six-year investigation into the effects of traffic on surfacings with deep transverse grooves are presented. In order to retain a high degree of roughness, the surfacing must have an average surface texture depth of 2 mm and no sand or stone elements susceptible to polishing near the concrete surface. It was possible to obtain similar surface texture depths using the roughening curing compound spraying machine developed by the Centre de Recherches Routieres. Roughness measurements carried out at different speeds (20 to 80 km/hr) showed that the coefficient of transverse friction between 20 and 90 km/hr decreases linearly as a function of the average surface structure depth, and is independent of the degree of polishing of the surfacing. Between 25 and 30 km/hr the coefficient of transverse friction is independent of the average surface texture depth, but its value depends on the degree of polishing of the aggregates on the surface. The dispersion of coefficient or transverse friction measurements is discussed, and an attempt is made to relate increases in the standard deviation of the coefficient of transverse friction to specific construction methods or traffic conditions. /CRIC/FESR/LCPC/A/RRL/

12. STUDY OF EFFECTS OF GROOVING ON PAVEMENT DETERIORATION INSPECTION OF GROOVED AIRFIELD PAVEMENTS. Air Force Weapons Laboratory /US/ Tech Rept No AFWL-TR-69-166, 36 pp, 30 fig, 3 ref. May70.

A study was made on the deterioration effects of deliberate grooving on airfield pavements. Grooving is done to reduce hydroplaning and skidding. Grooved pavements were inspected at four civilian and one military airfield. The inspection included portland cement concrete (PCC) runways at four airfields and asphaltic concrete (AC) runways at two airfields, all of which had been grooved within two years before the inspection. Grooves in all PCC runways were in excellent condition with no evidence of deterioration except in one case where numerous small popouts and weatherouts had occurred. Grooving had apparently contributed to an increase in these defects. The AC runways showed minor groove deterioration in some areas, and some obliteration of the grooves in one touchdown area. Rubber deposits in grooves have occurred in both PCC and AC pavements, but no removal of the rubber has been required. Grooving has not at present resulted in any significant deterioration of either PCC or AC runway pavements. Some closing of grooves in touchdown areas of AC surfaces can be expected, but this is not considered to be actual pavement deterioration. Where PCC pavements have previous popouts or other surface defects, grooving can be expected to increase these defects. PCC and AC runway pavements should continue to be inspected periodically to determine the long-time effects of grooving. /Author/

13. Brewer RA. EPOXY-ASPHALT OPEN-GRADED PAVEMENT AS A SKID-RESISTANCE TREATMENT ON THE SAN FRANCISCO BAY BRIDGE. Highway Research Board Special Reports No. 116, pp 42-47, 1 tab, 11 ref. 70.

    In late 1969, the Division of Bay Toll Crossing applied 1/2 in. thick epoxy-asphalt, open-graded pavement to two large test areas on the heavily graveled San Francisco-Oakland Bay Bridge. Two types of aggregate, air-cooled iron slag and granite, were used with 1/4 in. California standard open grading. This report describes the selection of epoxy asphalt as the skid-resistant treatment, its application, and its performance to date. In the 11 months since its application, the pavement has been tested for skid resistance and core pullout strength. In spite of minor localized raveling attributed to inadequate compaction in isolated areas due to cold temperatures at the time of placing and to other factors, the pavement promises fulfillment of the purpose for which it was selected: to provide increased skid and hydroplaning resistance, low increase in dead loads and superior structural properties. The accident history has improved substantially in the resurfaced areas. /Author/

14. Farnsworth EE. CONTINUING STUDIES OF PAVEMENT GROOVING IN CALIFORNIA. Highway Research Board Special Reports No. 116, pp 134-137, 1 tab, 2 ref. 70.

    The development of specifications for pavement grooving projects is presented. The normal groove is 1/8 to 1/4 in. in depth, cut by a blade 0.095 in. wide, spaced on 3/4 in. centers, and cut in the longitudinal direction. Minimum acceptable coverage of the specified pattern is 95 percent. Water and residue from the cutting operation are picked up by vacuum pumps. A maximum operational noise level of 86 DB on the A-scale is allowed. Before and after accident studies of pavement grooving projects are presented. Pavement grooving has resulted in an 85 percent reduction of wet pavement accidents in the grooved areas. /Author/

15. Beaton JL. MAKING HIGHWAYS SKID-PROOF. Civil Engineering ASCE, Vol 41, No. 3, pp 42-45. Mar71.

    Highway accidents are often caused, not by careless drivers, but by slippery pavements. Building skid resistance into roads is a job for the highway engineer. The theory of skidding indicates that skid-resistant roads should generate sufficient tire-road traction and have good drainage. Ideally, all new roads should have a long-lasting coarse-textured and gritty surface. The most important factor in making skid-resistant asphalt-concrete pavement is mix design. Polish resistance of the aggregate is also important, lest a surface rapidly lose its skid resistance. Skid resistance can be restored to such roads by using an asphalt-concrete blanket, a screening seal coat, or grooving. The surface finishing and texturing operation is the most important factor in making portland cement concrete skid resistant. To get a long-lasting, skid-resistant surface texture, the burlap-drag or the brooming method may be used. Restoration of skid resistance to existing roads may be done by applying a screening seal coat or an asphalt concrete blanket. Grooving has proved more effective than these two methods, however. /Author/

16. Farnsworth EE, Johnson MH. REDUCTION OF WET PAVEMENT ACCIDENTS ON LOS ANGELES METROPOLITAN FREEWAYS. California Division Highways, Federal Highway Adm. /US/ B-3-1.

    Improved pavement surface construction methods for new pavements and the use of pavement grooving and thin blankets for existing pavements are solutions to the wet pavement accident problem. Before and after accident studies of pavement grooving projects indicate a reduction of 85 percent of the wet pavement accidents. /Author/

17. PAVEMENT GROOVING AND TRACTION STUDIES. National Aeronautics & Space Adm /US/ Rep No. NASA-SP-5073; N69-20451, 521 pp. 69.

This collection of papers discusses reduction of aircraft and motor vehicle hydroplaning on runways and highways by pavement grooving. Methods, equipment, tests, benefits, disadvantages, etc., are discussed for the United States and Great Britain. Includes a description of three 16 mm films on hydroplaning. /HSL/

18. Mosher LG. RESULTS FROM STUDIES OF HIGHWAY GROOVING AND TEXTURIZING BY SEVERAL STATE HIGHWAY DEPARTMENTS. Pavement Grooving and Traction Studies, pp 465-504, 16 fig, 7 ref. National Aeronautics & Space Adm /US/ Rep No. NASA-SP-5073; N69-20451, 521 pp. 18Nov68.

In an effort to combat the increasing rate of automobile accidents, several state highway departments have been evaluating the pavement grooving process to increase the safety of their highways. The process and results of pavement grooving being performed at several locations are discussed. At locations where accident data are available, this technique appears to be very effective in the prevention of wet weather accidents; however, for most of the locations, accident data are not available.

19. Horne WB. RESULTS FROM STUDIES OF HIGHWAY GROOVING AND TEXTURING AT NASA WALLOPS STATION. Pavement Grooving and Traction Studies, pp 425-464, 26 fig, 4 tab, 9 ref. National Aeronautics & Space Adm /US/ Rep No. NASA-SP-5073; N69-20451, 521 pp. 68.

Results of studies of the skid resistance obtained on 30 different pavement surfaces installed at the NASA Wallops Station Airfield are discussed. Presented are transient peak, steady-state peak, and locked-wheel braking coefficients of friction for ASTM rib-tread and ASTM bald-tread tires and for new and worn production tires obtained under dry, wet, and flooded pavement conditions at vehicle speeds ranging from 10 to 80 mph. Results of limited vehicle spinout tests on a 500 ft radius highway curve are also included. It was found that the presently used method of making locked-wheel friction measurements to determine pavement skid resistance does not necessarily denote the true skid resistance of pavements under vehicle rolling or maneuvering conditions. Also, the skid resistance of smooth closed-texture pavements tends to be dangerously low under wet conditions when vehicles are operated at high speed with work tires. However, the more open textured pavements as well as the transverse and longitudinal groove pavements exhibited adequate skid resistance for the vehicle speed and tire conditions investigated.

20. Farnsworth EE. PAVEMENT GROOVING ON HIGHWAYS. Pavement Grooving and Friction Studies, pp 411-424, 9 fig, 2 ref. National Aeronautics & Space Adm /US/ Rep No. NASA-SP-5073; N69-20451, 521 pp. 18Nov68.

    Several years ago California Division of Highways accident analysis showed that some sections of concrete highways, especially on curves, were having an unusual number of accidents during rainy weather. Pavement-Grooving was applied to the surface of the roadway in an attempt to reduce the number of wet pavement accidents. Before and after accident studies of grooved areas have clearly shown the benefit of pavement grooving to the motorist. The accident data for 1964-1965 (before grooves) was 55 wet accidents; the data for 1966-1967 (after grooves) was two wet accidents. The longitudinal grooves act as "tracks", resisting lateral movement and stabilizing the vehicle. They also serve as quick surface drains to minimize any water buildup on the pavement.

21. Staughton GC. SOME MEASUREMENTS OF BRAKING FORCE COEFFICIENT ON SIX AIRFIELD TEST SURFACINGS. Ministry of Transport, London /UK/ RRL Rep LR 225, 23 pp, 12 fig, 5 tab, 17 phot, 5 ref. 69.

    To assess the skid resistance in wet conditions of a range of airfield surfacings, a series of tests was carried out on the runway at the College of Aeronautics, Cranfield. Locked wheel and peak braking force coefficients were measured for three concrete and three asphalt surfaces with the heavy load test vehicle fitted with an aircraft tire. Two of the concrete and one of the asphalt surfaces had been grooved, another asphalt surface had been dressed to improve their skidding resistance. It was found that: (1) The treatments given to both the concrete and the asphalt surfaces were beneficial in improving skidding resistance. (2) The peak coefficients were substantially greater than the locked wheel coefficients. (3) Generally, increasing the inflation pressure of the test tire from 276 to 1100 kg/m squared (40 to 160 lb/in. squared) reduced the peak coefficients. It reduced the locked wheel coefficients on the surface dressing and scored concrete sections. (4) The greatest tire damage was produced by the surface dressed asphalt and scored concrete surfaces when testing the locked wheel condition and using an inflation pressure of 1100 kg/m squared (160 lb/in. squared). /RRL/A

22. Dixon JC. TEXTURING OF CONCRETE PAVEMENTS. American Conc Paving Assoc Tech Bull, No. 1, 7 pp, 1 tab. 69.

The following methods of correcting existing portland cement concrete pavements exhibiting polished surfaces were explored: (1) treating with muriatic acid to restore fine texture and skid resistance, (2) grooving with a concut bump cutter, (3) using a Christensen concrete planer, (4) using a thin resurfacing with rubberized sand asphalt mixture, and (5) seal coating using slag aggregate. It was recommended that sand for use in concrete wearing surfaces contain a minimum of 25 percent silicon dioxide to prevent or delay polishing of concrete pavement surfaces. Skid data will be collected and studied before specifications are changed to require this minimum silica content. Methods of obtaining deeper textures were studied. One technique developed was a series of individual brooms mounted on a bridge to impart longitudinal texture in the plastic pavement. The best and most uniform texture seen was imparted by the conventional burlap drag. Several drags were employed in the paving train. Skid trailer tests will be conducted to evaluate these textures. The question of longitudinal versus transverse texture is discussed. Since transverse texture channels water quickly from the pavement, it minimizes hydroplaning. It is also effective in decreasing stopping distances in addition to having greater skid resistance. Research is needed to determine the effect of vehicle control on transversely textured pavements as compared to longitudinal texture.

23. Walz W. INFLUENCE OF THE COMPOSITION AND SURFACE TEXTURE OF ROAD CONCRETE ON ROAD HOLDING (IN GERMAN). Beton-Herstellung-Verwendung/ Germany/ vol 17, No. 10, pp 369-373, 402-406, 5 tab, 18 phot, 17 ref. 67.

It has not yet been determined whether and to what extent the composition of the concrete and the surface texture of concrete roads affect skid resistance both initially and after fairly long use by traffic. In an effort to answer these questions, cylinders 22.5 cm in diameter were made out of specified concrete having a varying aggregate composition and surface texture, and tested in the laboratory in a polishing machine with rotating rubber rollers. The best skid resistance was produced by a deep fine fluting with an opening width of approximately 2.5 millimeters. Apart from a high quality concrete, it is necessary to use an angular quartz sand of constant composition, for example 0/3 mm, as a fine size range and to keep the water-cement ratio as low as possible. /FG/RRL/

24. Maynard DP, Weller DE. TREATMENTS TO RETEXTURE A WORN CONCRETE SURFACE OF A HIGH-SPEED ROAD. Cement & Concrete Assoc, London /UK/ Technical Report TRA 409, 14 pp, 7 fig, 1 tab, 7 phot, 7 ref. Mar69.

Experiments were carried out on a section of the M1 motorway to determine the most suitable treatment to restore adequate skidding resistance to a worn concrete surface of a high-speed road. Measurements made during the initial three years of the experiment show that all the treatments had improved the sideway force coefficient at low speed (50 km/h) and that all the treatments markedly reduced the fall in skidding resistance shown by the untreated surface when the speed increased to 130 km/h. The best overall results were given by a diamond pattern of narrow grooves and by wide transverse grooves. /RRL/A/

25. Key EJ. TIRE WEAR TESTS ON AN OPEN GRADED MACADAM RUNWAY FRICTION COURSE. Ministry of Technology, London /UK/ Royal Aircraft Estab, pp 20, 5 phot, 2 tab, 4 ref. Aug67.

Aircraft trials were made to evaluate tire wear on the north/south runway at Farnborough after resurfacing with an open-graded Macadam friction course. A meteor MK.7 aircraft equipped with low pressure tires was used for the trials, which involved landings on the surface, under dry conditions, with maximum braking applied. For comparison, similar trials were made on the main runway, which had a grooved asphalt wearing course and was used as a reference surface. Thirty-five landings were made on each surface. Comparison of wear by two methods, measurement of groove depth and loss of tire weight, indicated that the wear was about 8-10% lower on the open-graded surface under the conditions of the test. /RRL/Author/

26. Beaton JL. SLIPPERY PAVEMENTS. Institute of Traffic Engineers, 39th Annual Meeting, 9 pp, 4 fig. Aug69.

The following subjects are discussed relating to slippery pavements: (1) measurement of pavement friction, (2) development of realistic skid resistance coefficients (reconditioning of work pavements so as to improve their friction levels), (3) construction techniques to insure specific friction levels of new pavements, (4) pavement wear and the factors involved in specifying aggregate and construction quality requirements to lenthen the service life of pavement surfaces, and (5) interface characteristics between the tires and wet pavements. Skid resistance surfaces are discussed and also the technique of grooving pavements. Before and after studies are reported related to pavement grooving. It is concluded that pavement slipperiness depends primarily on two factors: (1) coefficient of friction and (2) texture of the surface. At the state level in California, bituminous and portland cement concrete pavements are treated differently. Asphalt pavement construction is controlled by a combination end point quality and method specification using a mix design which is known to give a nonskid surface.

Portland cement concrete pavements are controlled by an end point coefficient of friction of 0.30 and the texture is controlled by requiring finishing with a burlap drag.

27. Burks AE, Maggs MF. RIGID PAVEMENTS AND THE ADVENT OF THE SLIP FORM PAVER. J Inst Munic Engrs /UK/ vol 95, No. 8, pp 237-239, 1 phot, 7 ref. Aug68.

The basis of design of concrete roads is briefly outlined, followed by a discussion of the present technical and economic situation, with particular reference to its competitive value. Some of the characteristics and advantages of using the slip-form paver on major roads are discussed and also its effect on methods of construction of minor roads and estate roads. The factors affecting the choice of reinforced or unreinforced concrete roads are considered. There is a brief discussion with recommendations on the specification of joint assemblies and joint groove forming methods and a description of the advantages offered by slip-formed, wet lean concrete as a base for concrete pavements. /RRL/A/

28. Weller, DE, Maynard, DP. TREATMENTS TO RETEXTURE A WORN CONCRETE SURFACE OF A HIGH-SPEED ROAD. Minstry of Transport, London /UK/ Road Research Laboratory /UK/ Rept LR 250, 28 pp, 5 fig, 5 tab, 9 phot, 7 ref. 69.

Experiments were carried out on a section of the M1 motorway to determine the most suitable treatment to restore adequate skidding resistance to a worn concrete surface of a high-speed road. Measurements made during the initial three years of the experiment showed that the treatments had improved the sideway-force coefficient at low speed (50 km/h) and that all the treatments markedly reduced the fall in skidding resistance shown by the untreated surface when the speed was increased to 130 km/h. The best overall results were given by a diamond pattern of narrow grooves and by wide transverse grooves; these were the most expensive methods tried but the cost would be considerably reduced if they were used on commercial scale.

Measurements will be continued on the sections to determine the long-term effect on the treatments. /RRL/

29. Mahone DC. REHABILITATION OF SLIPPERY ROADS. Highway Research Record, Hwy Res Board, No. 300, 6 pp, 6 fig, 3 tab, 4 ref. 69.

A survey is reported which was conducted by sending questionnaires to the 50 states and the District of Columbia to determine interest in measuring skid resistance. The survey indicated that 34 states and the District of Columbia are at present measuring skid resistance. Standard skid resistance test methods and adaptations are described. Minimum skid numbers and means of resurfacing are discussed. In order to rehabilitate the present slippery roads and to provide nonskid roads, it is believed that the following are needed: (1) a standard method of measuring skid resistance, (2) standard minimum skid numbers for various traffic conditions and geometric designs, and (3) economical means of providing skid resistance surfaces. Although it is true that isolated slippery conditions can be corrected by heater-planing, kerosene treatments, grooving, and superelevating, the author believes that the materials making up the mix are the most important ingredients affecting skid resistance. The state of Virginia has some slurry seal test sections that are now being evaluated for skid resistance. California has realized a phenomenal reduction in accidents by grooving the pavement. Test sections have been placed in which lightweight expanded shales were blended in limestone mixes, and a precoated polish-resistant aggregate was placed on a hot, plant, limestone mix. These methods show promise, but it will be several years before final judgment can be made.

30. CHECK THIS GROOVY PROJECT. Western Construction, vol 44, No. 12, p 59. Dec69.

A new grooving machine is being used on California highways to cut grooves in concrete pavement in areas where accidents occur due to slippery conditions. Longitudinal grooves were cut .095 in. wide and 1/8 in. deep, with 3/4 in. of space between groove centers. The new machine is equipped with a 5 ft wide arbor onto which are mounted 88 diamond saw blades. In a single pass, the machine cut a 5 ft wide swath. A vacuum unit is used in connection with the operation as California specifications require that cuttings and sludge from the grooving operation shall not be permitted to flow across shoulder or lanes or to flow in drainage facilities.

31. Stafford EY. GROOVING TREATMENT. Roadways, vol 15, No. 1, pp 7-8, Jan69.

    A reduction of 94.7% in accidents at a hazardous location on an interstate highway in North Carolina is credited to pavement grooving. Of 19 accidents on the same road curve, 18 took place on wet pavement. Benefit cost analysis indicates that the grooving project has more than paid for itself the first year. /HSL/

32. Sherman GB, Skog JB, Johnson MH. EFFECT OF PAVEMENT GROOVING ON MOTORCYCLE RIDEABILITY. California Division Highways, Bureau of Public Roads /US/, B-3-1. Nov69.

    A study was conducted to determine if the safety of the motorcyclist was impaired by pavement grooving and which pattern of those tested resulted in the least sensation to the cyclist. The six pavement grooving patterns most frequently considered for use on California highways were cut longitudinally into a relinquished PCC section of the state highway system. Seven motorcycles, ranging from one of the smallest legally allowed on California freeways to one of the largest used, were made available for evaluating these patterns. The evaluation was made by two experienced motorcyclists. The pavement grooving patterns, as tested in this study, did not present a hazardous riding condition to the motorcyclists. In general the lighter machines were more sensitive to the grooving patterns; however, none had a sensitivity level sufficient to cause a control problem. No individual grooving pattern was considered to be consistently superior from a motorcycle rideability standpoint. /Author/

33. Livneh M, Grinstein Y. THE INFLUENCE OF AGGREGATE SHAPE OF THE ENGINEERING PROPERTIES OF ASPHALT CONCRETE MIXTURES. Technion-Israel Institute Technology, Gerald Swope Research Fund, No. 014-340.

This research covers the influence of aggregate shape on the following mechanical properties of asphaltic concrete mixes: marshal stability, Hveem stability, grooving by a moving wheel, and triaxial shear. It is aimed to find the critical shape of aggregate and the rate of flaky aggregates which significantly change the mix quality. /TIIT/

34. Cahoon R. USE OF A RUMBLE STRIPE TO REDUCE MAINTENANCE AND INCREASE DRIVING SAFETY. Highway Research Board Special Reports, Special Rept 107, pp 89-98, 22 fig, 1 tab, 2 ref. 70.

Raised traffic markers have been in use successfully in California for many years. However, the main trouble with raised traffic markers is that they cannot be used in areas where snow removal is necessary because the snow plows cut them off. The Utah Department of Highways has been researching the possibility of recessing a design or texture to produce the same advantages as the raised markers. Textured paint stripes produced the following advantages: (1) Visibility was increased during critical conditions such as when it is dark and wet. (2) Paint life is increased. (3) A zip or buzz noise can be heard when the vehicle crosses over the type B rumble stripe and serves to warn the driver that he has entered another lane. Research is still continuing to determine the best design for a rumble stripe. The type B rumble stripe consists of 1 in. grooves running transverse to the flow of traffic. This stripe produces a noise but it cannot be cut economically with available equipment. Durability and cost will determine the best design.

35. SCARIFICATION OF AIRPORT RUNWAYS /IN FRENCH/ Explomat Actualities, Paris /FR/ No. 14, 95 pp, 2 phot. Mar69.

Results are given for tests carried out at Toulouse Blagnac

Airport with a view to reducing the slipperiness of runways by making grooves in the concrete surfacing with diamond-tipped tools. /LCPC/A/RRL/

36. CONCRETE GROOVING ON RUNWAYS DURING CONSTRUCTION. Contract Journal /UK/ Vol 232, No. 4715, pp 31, 40, 2 phot. Nov69.

    Details are given of a new texturing machine developed by the cement and concrete association and tried out at London airport on a short section of runway. /RRL/

37. Dale JM. PAVEMENT MARKING--DANISH STYLE. Better Roads, vol 40, No. 2, pp 28-29, & 31, 3 fig, 2 ref. Feb70.

    Danish practices, in terms of pavement markings, are outstanding from the standpoint of daytime delineation. All expressways and primary roads are marked with 20 in. wide edgelines, which are highly visible because of their size and their contrast with the predominantly used asphaltic-concrete riding surfaces. Thermoplastic material used consists of approximately 22 percent organic binder, 5 percent pigment and 73 percent fine and coarse fillers and aggregates. One of the things that distinguishes the Danish thermoplastic from its English and American counterparts is the use of synthetic aggregate called Sinopal in its manufacture. It is a very hard, white, skid resistant synthetic aggregate that has visibility characteristics, particularly when wet, that are superior to natural aggregates. Sinopal is principally used as an admixture to the aggregate fraction of asphaltic concrete to provide skid resistance and brightness to pavement surfaces. The thermoplastic material is a solid, is heated and melted and applied by a spreader box that is drawn along the road surface. A primer is employed when applications are made over portland cement concrete. Because of the rapid solidification time of the thermoplastic, it is not necessary to use warning cones. The life of the thermoplastic markings in Copenhagen is closely related to the traffic density on new highways in Denmark because edgeline, a grooving machine, is run along the edge to provide this line, which the thermoplastic application machine then follows. By depressing the edge marking in this fashion, a means for water runoff is provided and depression storage and ice patches are avoided.

38. Seymour WM. GROOVING PAVEMENT CENTERLINES FOR LANE DEMARCATION. Kentucky Department Highways, Division of Research, Res Rept 314, 5 pp., 6 fig. Oct71.

In late June 1969, the Kentucky Department of Highways contracted to have experimental, longitudinal centerline grooves, 15 feet long at 80 foot intervals, cut into both sets of dual lanes of a 2.7 mile portion of I-71 in Carroll County, When the centerline was painted in an otherwise normal way, the skip lines were alternately on grooved and ungrooved surfaces. The roadway was opened to traffic on July 15, 1969. On the night of April 1, 1970, or after nine months of traffic wear, an unusually heavy rainfall occurred at the test site. The grooved stripes were observed to be definitely superior in delineating the roadway centerline. The ungrooved stripes were faintly visible. It was also observed that water drained sufficiently well from the troughs of the grooves. No nightime or daytime dry weather observations were performed at that time. During the summer of 1970, the entire project was restriped. In general, the second striping corresponded with the first with respect to placement and coverage. During the early summer of 1971, a year after the first repainting, the stripes were again inspected. In general, the grooved stripes showed much more wear and (or) loss of paint than the ungrooved stripes, so that under all daytime conditions the grooved stripes were less visible than the ungrooved stripes. After a year of wear, the grooved stripes were better only during wet, nighttime conditions. For all other viewing conditions, grooved centerlines appear worn and would therefore require more frequent painting than ungrooved centerlines. /Author/

39. Sharp RS. STABILITY AND CONTROL OF MOTORCYCLES. J of Mech Engrg Science, London (UK), vol 13, No. 5, pp 316-329. Oct71.

Mathematical models of a motorcycle and rider are developed dependent on three alternative assumptions concerning the tire behavior. Stability characteristics are deduced and compared; and minimum requirements fot the model, greater than have been previously statisfied, are established. The most sophisticated of the models is used to calculate the effects of design changes, and the design implications are discussed. The main conclusions are that the fixed control characteristics of the motorcycle are unimportant, and the steady state response to steering torque is probably of secondary importance. A proper representation of the free control characteristics requires the use of at least an eighth order in which the tire relaxation property is included. /Author/

40. Sherman GB. GROOVING PATTERN STUDIES IN CALIFORNIA. Highway Research Record, Hwy Res Board, No. 376, pp 63-64, 3 fig. 71.

Grooves can be cut into pavement in a longitudinal (parallel to the centerline), transverse, or skewed direction. All grooving (except for a few short experimental sections) to date on California highways has been performed in a longitudinal direction. This leads to increased lateral stability and tends to guide the vehicle through a critical curve area. Various patterns are commented on and illustrated.

41. Lauritzen OL. PAVEMENT GROOVING AND EXPERIENCE ON WASHINGTON STATE HIGHWAY. Northeast Road & Street Conf Proc, pp 78-92, figs. Feb71.

Pavement grooving (1) increases the skid resistance quality of the pavement by providing a higher coefficient of friction and by resisting lateral vehicle movement through the interlocking offered between the pavement grooves and tires, and (2) provides an additional escape route for excess water on the pavement and an audible warning to the driver when entering a curve. The use of pavement grooving is effective on worn or smooth concrete pavement where curvature and wet pavement contribute to a large number of accidents. /Author/

42. Horne WB. TIRE HYDROPLANING AND ITS EFFECTS ON TIRE TRACTION. Highway Research Record, Hwy Res Board, No. 214, pp 24-33, 14 fig. 68.

This paper first discusses the buildup of fluid pressure in the tire-ground, footprint region of wet pavement that can lead to three distinct types of traction loss, namely, dynamic hydroplaning, viscous hydroplaning or thin-film lubrication, and the reverted rubber skid. The paper then discusses how pavement surface texture, pavement water depth, tire tread design, vertical load, and tire inflation pressure affect fluid pressure buildup in the footprint. Finally, two promising methods for alleviating fluid pressure buildup are discussed. These methods are pavement grooving and air jets placed in front of tires. /Author/

43. Hiss JG, Brewster DR. THE INFLUENCE OF JOINT WIDTHS AND SPACING ON PAVEMENT RIDING QUALITIES. New York State Dept Transportation, Bureau of Physical Research, Res Rept 68-7, 18 pp, 9 fig, 2 tab. Jul68.

The influence of transverse joint width and spacing on pavement riding quality was investigated to determine if it was possible to redesign transverse joints, thus improving joint sealer performance without affecting riding quality. During a field test, pavement roughness and noise levels were measured for joints from 3/8 to 1-1/2 in. wide, spaced on 40 ft and on 60 ft-10 in. centers. It was found that (1) increase in roughness due to varying the groove width was small, and did not affect riding quality; (2) no difference in roughness resulted from reducing spacing between joints; and (3) although increase in noise level measured by sound recording equipment was negligible, the human ear definitely detected sound caused by joints of 7/8 in. width or more when spaced 60 ft-10 in. apart, and of 5/8 in. width or more when spaced 40 ft apart. /Author/

44. Weller DE, Maynard DP. METHODS OF TEXTURING NEW CONCRETE ROAD SURFACES TO PROVIDE ADEQUATE SKIDDING RESISTANCE. Ministry of Transport, London /UK/ RRL Rept LR 290, 74 pp, 17 fig, 19 tab, 20 phot, 7 ref. 70.

The development of various methods for texturing the fresh surface of high-speed concrete roads is discussed. The performance is reviewed of various roads including those textured by the type of wire broom specified in the current ministry of transport specification for road and bridge works. The rate of wear and the skidding resistance of slow and fast lane surfaces are examined. An examination is also made of the effect of the initial texture imposed on the rate of change in skidding resistance with increase in speed. Recommendations are made for future work to continue the development of various methods of texturing. /RRL/A/

45. Bald J. ANATOMY OF A JACKKNIFE. Fleet Owner, vol 66, No. 1, pp 61-66, 1 fig, 2 phot. Jan71.

The basic cause of any jackknife is a twisting moment set up within the system by unbalanced propelling and resisting forces. Whenever the twisting moment exceeds the resisting moment as developed by the tires on the road surface, a jackknife is probable, as jackknives are caused by skidding. Six basic types of skids are front wheel, rear wheel, all wheels, spinout, power skids, and hydroplaning. As a rule of thumb measurement, hydroplaning will occur at nine times the square root of the tire pressure. Some factors involved in jackknifing are: driver, vehicle, maintenance, brake system, load, tire condition, road surface, weather, and panic stop situation. Major points of the booklet, "Keep Rolling with Safety in Winter Weather", published by the National Safety Council are given. Precautions to take to avoid jackknives are discussed. This pertained to driver education, tire tread and pressure, brakes, road surfaces, and friction coefficient. The National Highway Safety Bureau is currently proposing regulations requiring more stringent brake performance capabilities along with "anti-lockup" systems to be installed on both tractors and trailers. Next to a front tire blowout, the typical road driver fears the jackknife most.

46. Waters DM. THE AERODYNAMIC BEHAVIOR OF CAR-CARAVAN COMBINATIONS. City University, London /UK/, Dept of Aeronautics, Proc First Symposium on Road Vehicle Aerodynamics, 18 pp, 13 fig, 10 ref. 70.

Wind tunnel test data on a 1/16 scale car-caravan combination show the influence of various caravan design features on the overall drag and lift of the combination. From this the general conclusions were that: (1) rounding the forward edges, (2) sloping the forward face rearwards from the bottom, (3) reducing the gap, and (4) using guide vanes down the rear vertical edges would contribute to reduced drag. A low drag caravan incorporating these features showed a small improvement 6-10% in drag over the basic caravan. Some yaw data on the basic caravan alone is also presented indicating a center of pressure for side force a little ahead of the center of side area. This creates a destabilizing effect which increases with speed. /RRL(A)/.

47. JACK-KNIFE CONTROL BY BRAKING. Motor Transport /UK/ vol 99, No. 3223, p 8. Jan67.

The future automation of road vehicle brakes to prevent skidding is discussed, with the emphasis on reliability. A new air proportioning valve is being developed which reduces the input/output ratio so as to regulate the degree of braking according to the load carried, thus reducing instances of overbraking and subsequent jackknifing of unladen vehicles. Control of the vehicles when braking is also rendered simpler, and deceleration can be quicker and safer. /RRL/

48. Sabey BE, Lupton GN. PHOTOGRAPHY OF THE REAL CONTACT AREA OF TYRES DURING MOTION. Ministry of Transport, London /UK/ Report No. LR 64, 18 pp, 4 fig, 6 phot, 1 tab, 2 ref. 67.

A new technique is described of photographing the contact patch of a tyre on a moving vehicle by means of an optical system which enables the real area of contact on either a dry or wet glass surface to be ascertained. The vehicle tyre runs over a glass plate set into the surface of the Road Research Laboratory's test track.

By using a prism arrangement below the plate and photographing from beneath at angles greater than critical angle for glass to water or glass to air interface, a clearly defined area of contact can be obtained. A sheet of Perspex is used to protect the glass surface from scratches during tests. Preliminary tests with normal running tyres have established the test procedure necessary to obtain clear and precise photographs at speeds up to 45 mile/hr. Measurements of the records obtained show substantial reduction in contact length with increased speed. /RRL/A/

49. Kullberg G, Nordstrom O, Magnusson G, Formgren C. STUDIES OF BRAKING ABILITY AND DYNAMIC STABILITY DURING BRAKING OF PASSENGER CARS WITH CARAVAN TRAILERS. Statens Vaginstitut Reports /Sweden/ No. 93, pp 45-95, 24 fig. 67.

Conditions concerning braking ability and dynamic stability during braking of light vehicle combinations are reported. A light vehicle combination means here a vehicle combination consisting of a car, the maximum weight of which does not exceed 3500 kg, and a trailer with one axle or one bogie. Dynamic stability during braking is studied in different cases of not ideal braking force distribution for the towing vehicle and the trailer. The braking ability of light vehicle combinations is dealt with starting from the influence of different vehicle parameters. Certain characteristics of trailer brake systems are also described both in general and especially for five different types of systems. /RRL/A/

50. Kullberg G, Nordstrom O, Magnusson G, Formgren C. STUDIES OF DYNAMIC DRIVING CHARACTERISTICS OF PASSENGER CARS WITH CARAVAN TRAILERS. Statens Vaginstitut Reports /Sweden/ No. 93, pp 8-45, 22 fig, 2 phot, 17 ref. 67.

A light vehicle combination means a vehicle combination consisting of a car, the maximum weight of which does not exceed 3500 kg, and a trailer with one axle or one bogie. Studies were carried out on one hand with a mathematical vehicle model; on the other with field tests. The mathematical vehicle model was adopted

to study the effects of different vehicle parameters on the dynamic stability of the vehicle combination. This study started with a vehicle combination consisting of a passenger car of a size common in Sweden and weighing about 1200 kg and a trailer weighing 850 kg, and with data typical for a trailer of that size. The influence of some parameters was studied by varying these and keeping all other data constant. At the field tests two different towing vehicles weighing 2100 kg and 1260 kg were used together with a trailer whose weight varied between 1000 kg and 1300 kg. To make possible a comparison between calculated results and results obtained at field tests, those vehicle combinations were also studied with the mathematical vehicle model. /RRL/A/

51. BRAKE CONTROL CAN STOP JACK-KNIFING. Motor Transport /UK/ vol 100, No. 3248, 8 pp, 1 fig, 1 phot. Jul67.

    A modified version of the "antilock" brake control system to prevent wheel locking and skidding when braking on a poor road surface is described. The new design can be fitted to the driving axle of any rigid or articulated commercial vehicle equipped with air-hydraulic or full-air brakes. Tests showed that the stopping distance is considerably reduced when the anti-skid device is in operation. /RRL/

52. Hope FJ. BRITISH PATENT 1,075,802. ANTI JACK-KNIFE DEVICE FOR USE WITH FIFTH-WHEEL COUPLINGS PARTICULARLY ON ARTICULATED VEHICLES. Patent Office, London /UK/, 5 pp, 12 fig. Jul67.

    The invention consists of a fifth wheel coupling for an articulated vehicle, comprising a tractor and a trailer and having a means for resisting jack-knifing of the vehicle. /RRL/

53. Fuller SL. PAVEMENT CUTTING TO IMPROVE SKID CHARACTERISTICS OF PAVEMENTS. Florida Dept of Transportation, Bureau of Public Roads /US/ M-9-66.

    The effect was determined of pavement texturing on increasing pavement skid resistance and maintaining adequate skid resistance under the influence of vehicular traffic. A secondary objective was evaluation of the effectiveness of the texturing patterns as a warning device to vehicle operators by increasing vehicle vibration and noise. Two texture styles were tested at seven locations on both bituminous and portland cement concrete pavement. All surfaces were textured by a special diamond studded cutter in a transverse pattern. The two-year study concluded that transverse pavement texturing was only slightly effective on portland cement concrete and ineffective on bituminous concrete pavements. Furthermore, the textural patterns utilized were not suitable as highway warning devices. /BPR/

54. Simms, GE. ANTI-SKID GROOVES COMBAT HYDROPLANING. Pub Works Vol 96, No. 12, pp 7-86. Dec65.

Bump cutter equipped with 120 diamond impregnated saw blades mounted on horizontal shaft and powered by a 56 hp engine was used to cut longitudinal grooves in pavement of Western Highway with high accident rate due to hydroplaning cars. Cutter's 12 in. diameter diamond blades were spaced 0.25 in. apart, cutting 24 in. wide swath of 0.125 in. deep grooves at 5 lineal ft/min.

55. Hilgers, HF. SLICK WHEN WET. Texas Highw, Vol 10, No. 1, pp 8-10. 63.

Sawing equipment with 42 circular diamond blades was effectively used to increase the skid resistance of a nine-year-old, highly polished concrete pavement in San Antonio, Texas. The method was preferred to the acid, epoxy, polyester resin or slurry seal techniques which were found to be ineffective or uneconomic. Longitudinal grooves 1/8 in. deep and 3/16 in. apart were cut in 24 in. strips at a cost of 4.26 cents per square foot.

56. McCullough F. FIELD EVALUATION OF THE SAW CUT METHOD. Texas Highw, Vol 10, No. 1, p 10. 63.

Before and after tests were made of the friction coefficient of a concrete surfacing treated by this method (see preceding Abstract). Results showed that the stopping distance of a vehicle traveling at 30 mile/hr was reduced from 94 to 72 ft after the sawing of grooves and the friction coefficient on a wet surface was increased from 0.32 to 0.42; on a dry surface, the friction coefficient remained 0.7. The main benefit of the grooving, however, was that though skidding still occurred afterwards, the vehicle always skidded in a straight line.

57. Eshlerman RL, DeSai S, and Hanify DW. Engineering Mechanics Div, ITT Research Institute. ANALYTICAL-EXPERIMENTAL RESPONSE OF ARTICULATED VEHICLES. Fleet Owner. Society of Automotive Engineers. Combined Com Veh Engng & Operations and Powerplant Mtgs, Chicago, Ill. June 18-22, 73.

Analytical-experimental studies were conducted on a tractor-semitrailer vehicle performing prescribed lane-change maneuvers. This paper shows the validation of the Articulated Vehicle Dynamics Simulation model (AVDS II) with full-scale tractor-semitrailer field tests. Experimental data on the tractor trajectory and braking were used as computer input, and the simulation model response results were compared with the vehicle responses from the experimental tests on a time-transient basis. Analytical-experimental validation is shown for varied vehicle speeds and braking during maneuvers.

58. This item reflects research underway as listed in Highway Research in Progress:

PAVEMENT GROOVING 26 207037
Res Agy: Pennsylvania Department Transp
Investigator: Mellot DB, Shaffer RK
Started July 69 Status: Active Sept. 72 Est. Compl: 73
Cost Estimates Curr yr Total

Evaluation is made of 38,469 square yards of longitudinal grooving to: (1) evaluate the technique of pavement grooving, (2) determine the improvement in skid resistance, (3) record the reduction in traffic accidents, and (4) evaluate the durability of the grooved pavement.

APPENDIX B

STATISTICAL BACKGROUND

Very often in research, a quantitative decision must be made about an experiment on the basis of sample information. Such decisions are based on statistical comparisons.

In reaching these decisions, assumptions about the test samples are made. These assumptions may or may not be true and are called statistical hypotheses. For example, if one wants to decide whether one pavement is better than another, a hypothesis is formulated that there is no difference between the performance of the two pavements. This hypothesis is called the null hypothesis and is signified by H_0. The alternate hypothesis that there is a difference is noted as H_1. The procedures that enable one to accept or reject a hypothesis, i.e., determine if the samples differ significantly, are often termed tests of significance.

If a hypothesis which is true is rejected a Type I error is committed and conversely if a false hypothesis is accepted a Type II error is committed. In either case there has been an error in judgement.

For the test of hypotheses i.e. if the rule of decision is to be good, the experiments should be so designed to minimize errors. In practice this becomes complex, generally because a decrease in one type of experimental error is often accompanied by an increase in another experimental error. One error type may be more serious than another, thus a compromise is reached that favors limiting the more serious error. The only way to decrease errors (assuming acceptable instrumentation accuracy) is to increase sample size which in many cases is practically or economically not possible.

In testing a given hypothesis, the maximum probability that one is willing to risk the making of Type I error is called the level of significance. This probability is signified by α and it should be determined before the sample is drawn so that the resulting decision will be less subject to researcher bias. There is no fixed rule to determine what level of significance is to be used, but customarily and α of .05 or .01 is employed. Thus, if a test of significance does not yield a .05 or 5% level, the hypothesis is said to be rejected at the .05 level of significance. Thus, there are 5 chances in 100 of rejecting the hypothesis when it should be accepted, or there is 95% probability that a correct decision has been made.

Commonly in research a relationship is thought to exist between two or more variables. Thus, a method is sought of expressing the form of the functional relationship. Wanted is not only a mathematical function which relates how the variables are interrelated, but also the precise value of one variable if the values of associated variables are known. The procedures used to accomplish these two objectives are termed regression methods and correlation methods. If only two variables are involved this is noted as simple correlation and simple regression. When more than two variables are present they are termed multiple correlation and multiple regression. In the present study multiple correlation and regression techniques are used.

It may be postulated that the experimental variables under investigation possess some basic, or causal interrelationships. However, as often is the case, known facts are such that the basic variables and basic mechanisms are not known with certainty. Under such circumstances the tools of regression and correlation can prove useful as analytical and predictive procedures.

However, one must use caution when utilizing these methods. This is due to a particular functional relationship being hypothesized and a specific mathematical procedure employed. Thus, the assumption that a causal relationship exists is not always valid. If a function has been found that fits the experimental data, at times the scientist is not in a position to infer that a change in one variable will cause a change in another variable. In the final analysis the only person who can safely say that the variables used and the mathematical functions employed are valid is one who is well trained in the subject matter and the methodology which was employed in the experiments. Thus, the statistical analysis is only another tool to help in analysis and interpretation of data.

As noted previously, correlation provides a method of estimating a functional relationship among the variables in question. However, there naturally arises a related matter when discussing the variables. It is: What is the degree of association among the variables? The techniques used to predict the association between variables are called correlation methods.

This concept of correlation is closely related to regression. Therefore, for a given regression equation, it is expected that a correlation method will reflect how well the regression equation fits the available data. Stated in another manner, correlation methods tell how closely the regression curve follows the sample points. When a multiple regression has been fitted to the experimental data, the measure of "goodness of fit" is desired. In this case a correlation index R^2 can be defined as the proportion of variance of the dependent variable y that can be attributed to its linear regression on the independent variable x. Or stated in another manner,

$$R^2 = \frac{\text{sum of squares due to regression}}{\text{corrected sum of squares}}$$

Thus, if the sample points closely follow the regression curve (a high correlation) the value of R^2 will approach 1.0. Conversely, if the sample data contains large amounts of variation causing wide dispersion about the regression curve, R^2 will approach 0. Generally, R^2 of .7 or above is considered "good" in this study. If R^2 is to be acceptable, it should possess the following characteristics:

(1) R^2 should be high when the degree of association is high and small when association is low.

(2) It should be independent of the units in which the variables are measured.

The study employed the techniques of regression and correlation to achieve the best possible function for the variables in question and yet provide a high degree of correlation and retain a relatively simple functional expression for practical implementation.

The three equations obtained from the regression analysis were presented in Chapter III and were incorporated into the simulation models. A summary of the simple statistics of these equations is given below. The equations and their exponents are given by Equations 2 and Table 2.

Free Rolling Model (High-Speed Data Included)

N = Number of data points = 745
R^2 = Correlation index = 0.990
Mean = 350.72 lbs.
Standard Deviation (S) = 50.74 lbs.
Min. F_G value 83.5 lbs.
Max. F_G value 1400.0 lbs.

Braking Model
$N = 1710$
$R^2 = .903$
Mean = 770.47 lbs.
S = 111.18 lbs.
Min. F_G value 70.6
Max. F_G value 1575.7

Motorcycle Model
$N = 284$
$R^2 = .903$
Mean = 770.47 lbs.
S = 31.18 lbs.
Min. F_G value 0.0 lbs.
Max. F_G value 403.9 lbs.

Free Rolling Model (No High Speed Data)

$N = 686$

$R^2 = .944$

Mean = 454.22

$S = 61.11$

Min. F_G value 83.5 lbs.

Max. F_G value 1400.0 lbs.

APPENDIX C

MOTORCYCLE RIDER'S OPINIONS
ON PAVEMENT GROOVING

Selected letters expressing rider opinions about the effects of pavement grooving on motorcycle handling.

AMERICAN MOTORCYCLE ASSOCIATION
P.O. BOX 141, WESTERVILLE, OHIO 43081
Telephone (614) 891-2425

May 1, 1974

Mr. J. E. Martinez
Texas Transportation Institute
Texas A&M University
Structural Research
College Station, Texas 77843

Dear Mr. Martinez:

Enclosed you will find photocopies of the letters we have received from motorcyclists concerning their experiences with rain grooving.

We have noticed that the leading motorcycle magazines, such as CYCLE GUIDE, CYCLE, and CYCLE WORLD, all headquartered in southern California, often include in their road test materials comments about the particular motorcycle being tested and its reaction to rain grooving. It might be beneficial for you to contact the editors of those publications to get their subjective interpretations.

If we can be of further assistance, please feel free to call upon us.

Sincerely yours,

Gene Wirwahn
Legislative Director

GW/fh
Enclosures

To satisfy DOT requirements for technical report, this letter has been retyped from original.

U. S. DEPARTMENT OF LABOR
MANPOWER ADMINISTRATION
BUREAU OF APPRENTICESHIP AND TRAINING

Room 203 Carroll Building
428 East State Street
Trenton, New Jersey 08608
(609) 599-3511 Ext. 385

May 29, 1973

Mr. Frederick DePhillips
Assistant Commissioner of Highways
of New Jersey
1035 Parkway Avenue
Trenton, New Jersey 08625

Dear Mr. DePhillips:

I wish to thank you for your cooperation and the prompt action you took regarding our conversation about erecting a motor cycle warning sign for grooved highways. I noted the first sign to be erected in New Jersey was at the Clinton Point Intersection of Interstate Highway 78 and 31 heading north.

I'm assuming that you will also make available a motor cycle warning sign in the same area heading south. Also, another very dangerous area is at the top of Budd Lake Hill in Morris County, Route 46 heading west. Your interest in the safety of highway users is deeply appreciated, and I'm sure that by the erection of these warning signs to the oncoming cyclist will do much to eliminate accidents.

I am forwarding a copy of this letter to Mr. Russell E. March, Executive Director of the American Motor Cycle Association, who had demonstrated great interest in the promotion of safety for the motor cycle industry. Your continued cooperation will be greatly appreciated.

Yours very truly,

John B. LaPorta, Representative
United States Department of Labor

cc: Russell E. March

To satisfy DOT requirements for technical reports, this letter has been retyped from original.

1010 E. Avenue
Coronado, California 92118

February 7, 1973

A.M.A.
Box 141
Westerville, Ohio 43081

Gentlemen:

BMW Riders of America have encouraged members to write in about rain grooves. Here are some of their letters which I hope may help you, as suggested in the February AMA REPORT.

After several years of working with local highway sources I suspect grooves are here to stay. Statistical evidence seems to be on their side.

There seem to be two problems for motorcyclists: (1) they may be caught unawares of the grooves and react unsafely to the shaking... a problem that signs should help, and (2) the grooves seem especially hazardous if a cyclist has a flat tire, since the tire when deflated seems even more likely to follow the grooves. Several BMW riders, including me have experienced this unhappy situation.

Very truly yours,

John E. Hermann

To satisfy DOT requirements for technical report, this letter has been retyped from original.

American Motorcycle Association
P. O. Box 141
Westerville, Ohio 43801

RE: Your letter dated June 7, 1973

Dear Mr. Wirwahn:

I have received some response to my letter to Raymond T. Schuler concerning the use of rain grooves. State Senator James Donavan was the first to contact me, stating that he had been in touch w/Mr. Schuler's office and he was promised that something would be done.

June 2nd, I received Mr. Schuler's response while he would not confirm the fact that the particular curve that has been rain grooved was poorly designed in the beginning, he did admit that there is a hazardous situation for light cars and motorcycles.

Signs reading "GROOVED PAVEMENT" have been ordered and will be erected on Route 8 as soon as they are received. To this date, they have not been installed.

Now if we can get them to post signs for steel decked bridges. I have just returned from a trip through every state east of the Mississippi (incl St. Louis) on motorcycle and Pennsylvania was the worse state as far as posting Steel Decked Bridges. Several times I encountered them in the <u>middle</u> of a curve!

In response to your last paragraph - I have been subscribing to the AMP news and you should have received my membership application by now.

Sincerely yours,

Scott F. Fancett

To satisfy DOT requirements for technical reports, this letter has been retyped from original.

3-25-72

Att. Ralph Nader ---

Grooved freeways may be safer for cars, but they are definently (sic) unsafe for motorcycles. Obviously, we m.c. riders were not considered in exicuting (sic) this project. Apparently we don't count. Please see what you can do. My M. C. acts squrelly (sic) as hell on those grooves. (They are not a groove!)

Thanks for any help.

--- Bill Schmidt
406 N. Windsor Bl.
Hollywood, Calif.
90004

To satisfy DOT requirements for technical report, this letter has been retyped from original.

1/3/73

Dear Sirs,

This letter concerns an experience I had with a stretch of grooved highway. I now live in Madison, Wis., but several years ago I was doing some riding in and around Washington, D.C. On a Sunday afternoon in June of 1971, I was riding north on I-95 from Virginia Beach, Va. to the District of Columbia. About twenty five miles south of the intersect of I-95 with the capital bellway, I came upon a section of grooved highway. Not only was it unmarked, but it was the first such stretch I had ever encountered. Instantly, I felt as if I was riding the bike on a tightwire. My machine wobbled around and I was scared silly. I let up on the throtle (I didn't chance the brake) and the bike wandered into the next lane! Luckily, I missed the car in that lane. (I-95 is always packed on summer Sundays in this stretch in the afternoons) At this point, the grooved section ended. Needless to say, everyone who had been nearby was honking at me. I was so relieved to be unscathed that I didn't care what they were doing. I even stopped and walked back to have a look at the offending stretch to see what it was. My immediate thought upon seeing the grooves was that the persons responsible could never have ridden motorcycles. To my mind there is <u>no</u> excuse for the presence of this type of highway. I had eight months and 3000 miles of total cycle riding experience at the time. The day was sunny, 85°, and the road was as dry as the Sahara.

Yours,

David W. Heumann

To satisfy DOT requirements for technical report, this letter has been retyped from original.

April 30, 1972

BMWRA
P.O. Box 3036
San Diego, Calif. 92103

Gentlemen:

I would like to enlist the support of the BMWRA in taking a strong stand to stop any further grooving of our highways and to get state highway departments to alleviate the problem by either eliminating the parallel grooving entirely or to demonstrate through research that some other grooving procedure or surface texture would provide safe driving conditions for motorcyclists as well as motorists.

I ride a motorcycle on the freeways and have found that grooved highways literally throw me out of control when I am travelling at freeway speeds. And even though I haven't spilled my motorcycle on one of the grooved sections or highway the unstable steering that I experience always gives me the feeling that I might get completely out of control. As you said in your News Letter, California Highway Patrol statistics show a 340% increase in motorcycle accidents on the grooved roads.

Whenever I traverse one of the grooved sections I find that I am forced to slow down and concentrate on "just keeping upright". I have talked to many cyclists about this problem and have found that some of them have developed precautionary tactics that they employ whenever they encounter the grooves. One rider told me that:

- he always slows down to about 40 mph
- he quickly views the shoulder and if it is paved and has sufficient room he drives on it to bypass the grooved section.
- if the shoulder is not paved or too narrow he then weaves back and forth to avoid being hooked in the tracks.

But what about the rider that comes upon a grooved section at night. If his bike is particularly susceptible to the grooves he may be in trouble before he can slow down sufficiently to get the bike under control. Whatever action the driver takes, you can be sure will be disconcerting to the following driver.

When I discussed the problem with an official of the Highway Department in the State of Washington he told me that the decision to groove pavement was the result of a rash of one car accidents that occurred on turns during heavy rainstorms. He also mentioned that a major contributing factor to these accidents was excessive baldness of the tires. He said that cars that have reasonably deep grooving tread on their tires are seldom involved in this type of accident. He also stated that the Highway Department had asked the Seattle Police to test drive the grooved test section of highway to see whether they experienced any difficulty due to the grooved and they reported that they had not.

However, the police in this place have Harley 74's and I wonder if the combination of motorcycle, design and tire size. . . (lettering obliterated) . . . driver height not have influenced those results.

In any event it is my understanding that the State Highway Department is proceeding with plans to groove extensive portions of the freeway between Seattle and the Canadian border.

Before this is done I think that the Department of Transportation and Washington State Highway Department (another state so affected) should fund the study that answers the following questions:

1. To what extent has the one car accident rate decreased (if any) since the introduction of the new state law that requires adequate tread depth on all tires.
2. What is the accident rate of motorcycles in this state due to the grooved pavement.

3. What research has been done to determine whether some other surface pattern or perhaps some other grooving orientation (making the direction of the grooves cross the lane at a 45° angle) might not solve the spinout problem for motorists and still be acceptable to motorcyclists.

In the mean time, while the problem is being considered it would be prudent to install warning signs prior to each grooved section of pavement to alert motorcyclists about the hazardous condition.

The Department of Transportation and State Highway Departments must realize that motorcycling is on the upswing and in a few years may well compete with automotive travel. Lets not design our public throughways to favor the automobile.

Sincerely yours,

Robin H. Towne
BMWRA 870
2442 - 8th North #204
Seattle Washington 98109

To satisfy DOT requirements for technical report, this letter has been retyped from original.

APPENDIX D

TESTING EQUIPMENT

HSRI MOBILE TIRE TESTER

The HSRI mobile tire tester consists of a retractable test wheel mounted on the rear of a modified tandem-axle commercial tractor (shown in Figure 37) which serves as the test bed. The test wheel accommodates tires in a size range 6.45-14 to 9.15-15. A dead-weight vertical tire load (independent of the test bed) in the range 600 to 2000 pounds may be used. The test wheel is attached to the test bed through a transducer sensitive to longitudinal and lateral tire forces and aligning moment. Calibration tests show transducer accuracy to be approximately ± 1.5 percent of full-scale as calibrated "on truck" under all conditions of loading.

The on-board data acquisition system, consisting of an FM magnetic tape recorder and a light-beam oscillograph, is mounted in the sleeper portion of the tractor cab along with test wheel control instrumentation. Electrical power for the instrumentation is supplied by an on-board gasoline-fueled 6.4 KW AC generator. Other test data recorded are tread surface temperature (from an infrared radiometer mounted above the test tire as shown in Figure 38), test wheel angular velocity, and test bed velocity. These last two quantities yield a precise measure of test tire longitudinal slip.

The test wheel is driven by a hydraulic motor which allows test wheel speed to be varied independently of test bed speed. The hydraulic motor is controlled from the cab and operates in three modes: steady-state (constant) slip, slip varying linearly with time, and sinusoidal slip variation with time. The last two modes are controlled by automatic programs to cycle the longitudinal slip between adjustable limits in an adjustable time span.

Either braking or driving torque is developed by driving the test wheel at a rotational rate corresponding to a linear velocity less than or greater than the road speed, and has several advantages over braking by a conventional mechanical brake (drum or disk). A tire controlled by a mechanical brake exhibits extremely rapid lock-up after developing its peak braking force and the data is prone to spurious transients. The

FIGURE 37: MICHIGAN'S TIRE-PAVEMENT FRICTION TESTER.

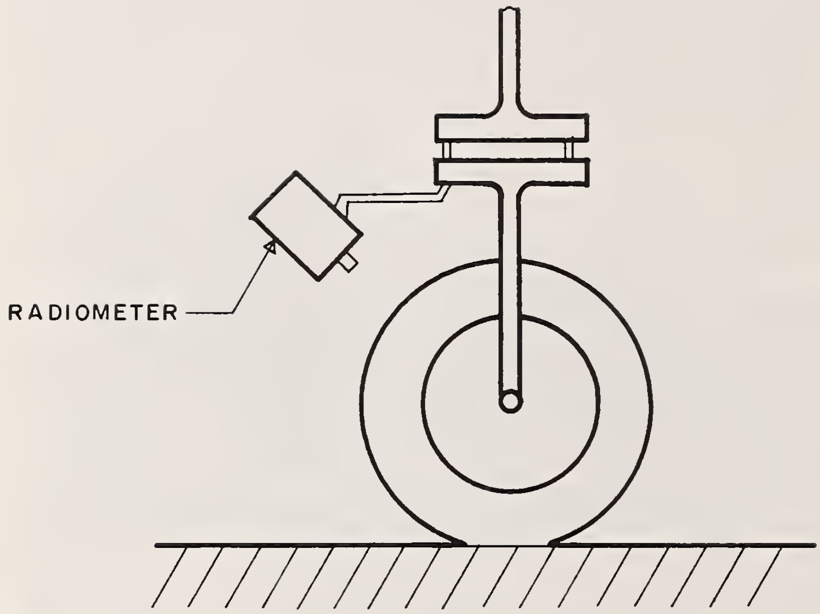


FIGURE 38 - LOCATION OF INFRARED RADIO-METER MEASURING TIRE TREAD TEMPERATURE DURING MOBILE TIRE TESTS.

mobile tire tester is able to precisely control test wheel acceleration and deceleration over the entire longitudinal slip range of tire operation (driving to free-rolling to locked wheel).

The performance characteristics of the mobile tire tester are tabulated below:

TEST BED

International COF 4000 diesel

Wheelbase	= 142 in.
Net hp	= 300 at 2100 rpm
Gross hp	= 318 at 2100 rpm
Max. GVW	= 45,000 lbs.
Max. speed	= 70 mph
Total present weight	= 23,687 lbs.

TEST WHEEL SPECIFICATIONS

Max. vertical load	= 2,000 lbs.
Max. braking torque	= 1,500 ft. lbs.
Max. steer angle	= 18^{o}

(With modification, angle can be increased to 26^{o}.)

Accommodates all tire sizes from 6.45 X 14 to 9.15 X 15.

LONGITUDINAL SLIP CONTROL SYSTEM

The Hydreco model 110 with a variable displacement pump drives the Hydreco motor (capacity 190 hp or 70 mph with F_x = 1000 lbs.) and will drive the test wheel at 100% wheel slip at 55 mph or 130% slip at 45 mph.

A steady-state lateral slip is achieved by presetting the tire-transducer assembly to a slip angle relative to the test bed. Longitudinal slip, via the hydraulic motor, can also be applied or the drive shaft disconnected from the test wheel for free-rolling lateral force measurements. The free-rolling wheel at zero degree slip angle is used to measure tire rolling resistance.

An additional feature is the on-board 540 gal. water tank with a remote-controlled gate valve and road surface delivery system.

T.T.I. TIRE TEST FACILITY

Additional data were acquired by the T.T.I. tire tester (Figure 39). The T.T.I. Tire Test Facility is designed to measure tire-pavement interface forces under various test conditions. Segments of pavement are employed rather than simulated surfaces.

The test tire is mounted on a retractable mechanism that is actuated by a low-friction bellows air cylinder and is controlled by an air-mechanical servo to maintain a preset vertical force. This mechanism will accommodate forces from 0 to 2,200 pounds with input accuracy of ± 20 pounds. The vertical force acting during the test is measured by the basic measuring means which is discussed later. The retracting mechanism is in turn mounted on a carriage which traverses the test surface horizontally. This carriage is powered by a unique electro-hydraulic/dead weight system. A pair of pressure and temperature compensated flow control valves are used to adjust and control a preset test velocity which has a range of a few inches per second to eight feet per second. The carriage also contains various controls and adjustments for setting preselected steer and camber angles. A removable disc brake is located in the hub mechanism to allow locked wheel or free rolling tests to be conducted.

All tire-pavement force measurements are made with an instrumented force plate located in the path of the carriage mechanism. Within the force plate, seven tension-compression transducers are disposed as shown in Figure 40. Each transducer has an omni-directional elastic flexure at each end which insures low cross-talk when arranged as shown. The total horizontal force parallel to the direction of travel is derived from the electrical signal of H1. The sum of L1 and L2 gives the total lateral force perpendicular to the direction of travel and the sume of V1 through V4 gives the total vertical force while the test tire is over the force

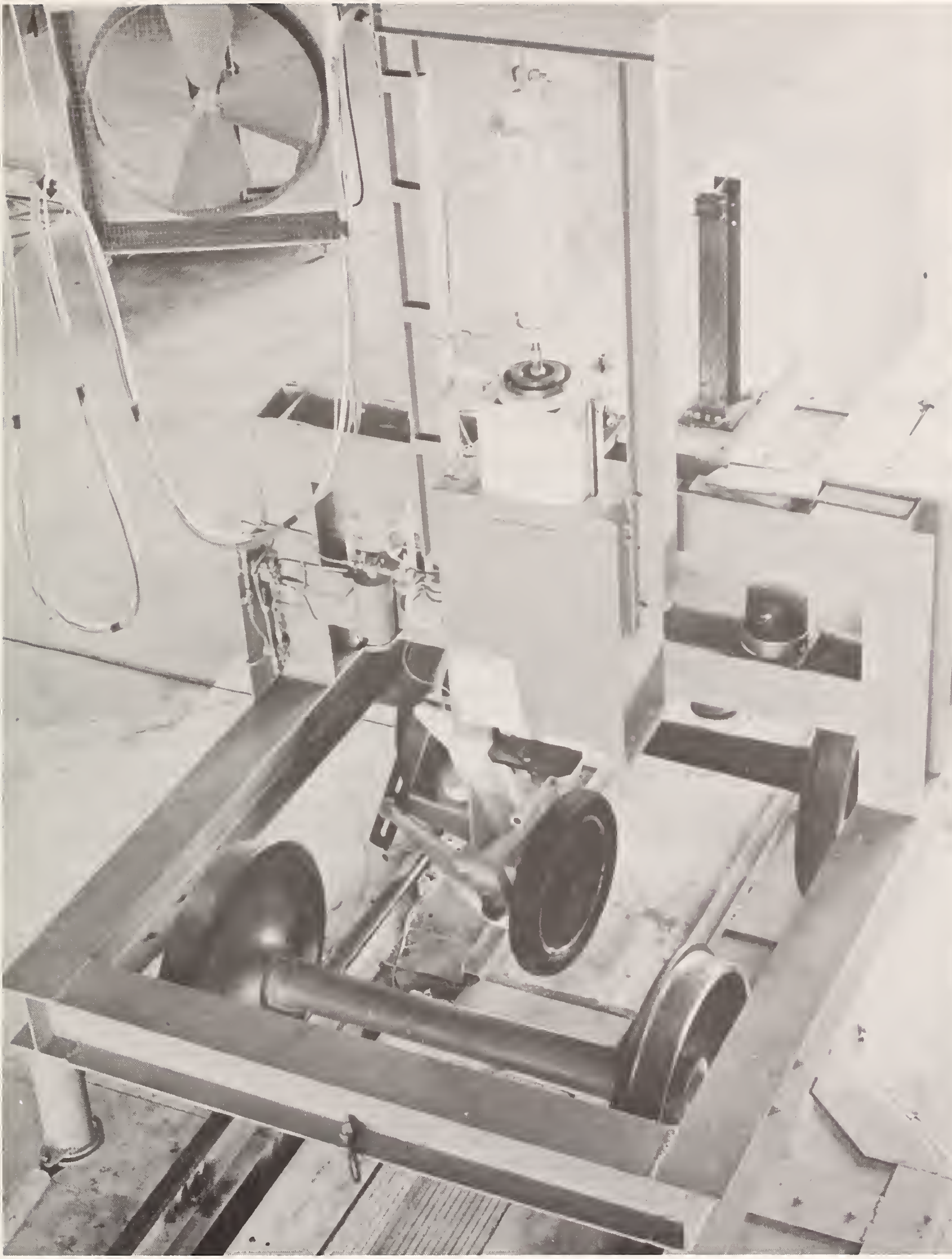


FIGURE 39: T.T.I. TIRE TEST FACILITY

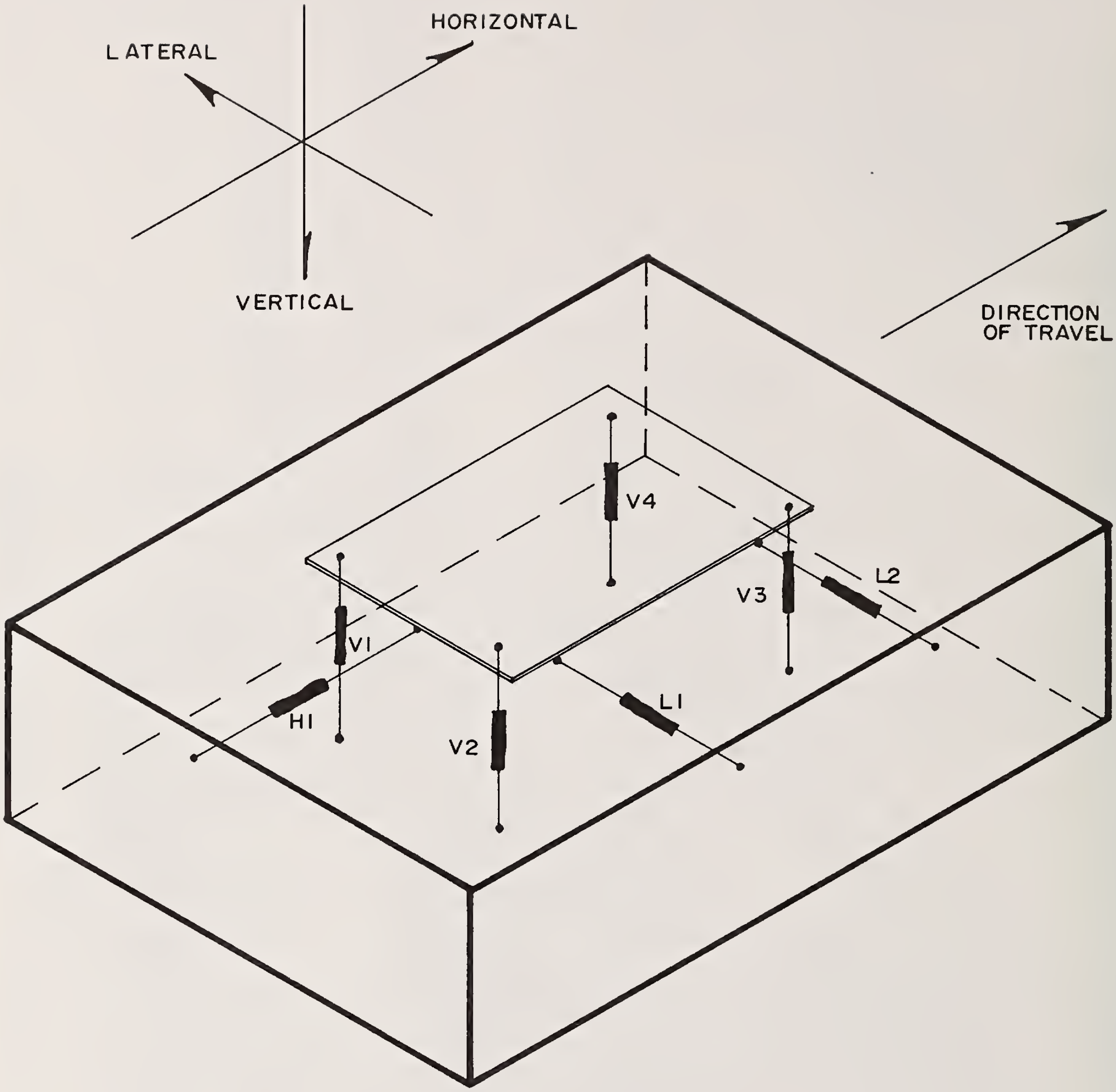


FIGURE 40 - SCHEMATIC SHOWING THE DISPOSITION SEVEN FORCE TRANSDUCERS WITHIN THE INSTRUMENTED FORCE PLATE.

plate. Physical calibrations of the individual transducers have shown non-linearity and non-repeatability errors of less than ½ of 1%. In-place calibrations show errors of less than 1%. The upper surface of the force plate is mounted slightly below ground level so that it can accept 18 inch X 66 inch prepared pavement sections. Such an arrangement allows practically any actual pavement type to be tested and does not require tests to be conducted on surfaces such as stainless steel belts, etc. Extensive attention has been given to waterproofing and draining of the force plate so that wet tests may also be conducted on the pavement materials.

The data acquisition and recording system has been designed to provide for minimum data turn-around time, which can be accomplished in approximately two hours. This system is contained in an adjacent air conditioned room which also houses the majority of the operational controls. After normal signal conditioning, the several electrical signals are digitized using a 16 channel analog-to-digital converter and immediately recorded on computer compatible digital magnetic tape. Calibration records are periodically recorded which also contain the necessary computer control information. All data are simultaneously recorded on a light beam oscillographic recorder for immediate visual analysis. Table 8 contains a complete list of all electrical signals which are routinely recorded and used in various computer data computations. Table 9 lists all the input test parameters which are available.

TABLE 8: LIST OF DATA CHANNELS AVAILABLE FOR RECORDING

CHANNEL	DESCRIPTION	RANGE	UNITS
1	Vertical wheel load	0 - 2200	lbs.
2	Horizontal frictional force	0 - 2200	lbs.
3	Lateral 1 frictional force	0 - 2200	lbs.
4	Lateral 2 frictional force	0 - 2200	lbs.
5	Test wheel rotational velocity	determined by carriage speed and wheel radius	rad/sec
6	Longitudinal position on force plate	0 - 66	in.
7	Hub height	6 - 18	in.

TABLE 9: INPUT TEST PARAMETERS AVAILABLE

NUMBER	DESCRIPTION	RANGE	UNITS
1	Test velocity	Approximately 1/4 to 8	ft/sec
2	Vertical load	0 - 2200	lbs.
3	Steer angle	-5 to +20	degrees
4	Camber angle	$\pm 20°$ or 0 to +40	degrees
5	Test tire type	13 to 34 outside diameter	in.
6	Pavement type		N/A
7	Test condition		N/A
8	Tire condition	locked or free-rolling	N/A

APPENDIX E

SIMULATION STUDY OF MOTORCYCLE RESPONSE TO PAVEMENT GROOVING

SIMULATION STUDY OF MOTORCYCLE RESPONSE
TO PAVEMENT GROOVING

Dennis T. Kunkel

Calspan Report No. ZN-5740-V-1

Prepared for:
Texas A&M University
Texas Transportation Institute
Structural Research Division
College Station, Texas 77843

October 1975

Calspan Corporation
Buffalo, New York 14221

FOREWORD

This report describes a brief study performed by the Transportation Safety Department of Calspan Corporation for the Texas Transportation Institute (TTI) of Texas A&M University during the period 29 May 1975 to 29 September 1975. This work was done in support of Contract No. DOT-FH-11-8267, "Effects of Pavement Grooving on Friction, Braking, and Vehicle Control." The Calspan internal authorization number was 364.

This report has been reviewed and approved by:

Edwin A. Kidd

Edwin A. Kidd, Head
Transportation Safety Department

The handling characteristics of all vehicles are affected in some way by pavement grooving. The effects of grooving on motorcycle handling can be particularly serious due to the motorcycle's lack of inherent roll stability in comparison with four-wheeled vehicles.

The intent of this study was to determine whether the negative effects of grooved pavement on motorcycle handling, as generally reported by motorcycle riders, could be minimized or eliminated through changes in motorcycle parameters. This was to be determined by simulating the response of a motorcycle to a grooved pavement section using a digital computer simulation. The simulation program used was the Calspan motorcycle dynamics computer simulation program, which was modified for this study. The program is described briefly in Appendix E and in greater detail in Reference 16. The modifications made to the program will be described later. The motorcycle data used for the simulation were chosen to approximate a Yamaha RD 350, which was the motorcycle used during full scale testing by TTI. The physical properties of the simulated motorcycle which are given in Appendix F came from three sources:

> Motorcycle inertial data and motorcycle tire data came from a data set for a Honda CB360G motorcycle, which is similar in size and weight to the Yamaha. This data set was originally prepared for use in Contract No. DOT-HS-4-00976 and reported in Reference 17.
>
> Motorcycle geometric data (wheelbase, rake, trail, etc) came from a road test of a Yamaha RD 350 B which appeared in the December 1974 issue of Cycle magazine (Reference 18).
>
> Rider weight was provided by TTI.

The simulated maneuver was the traversal of a section of grooved pavement by a motorcycle running in a straight line. Steering torque data were obtained in full-scale tests by TTI by means of a torque sensor located between the handlebars and front fork of the test motorcycle. This experimentally recorded torque signal was then digitized and used as a disturbance input to the motorcycle computer simulation.

The steering torque signal was applied in the simulation as a moment acting about the motorcycle's steer axis. The motorcycle simulation program was modified to permit the input of this external torque through the addition of two subroutines and revisions made to several others. One of the new subroutines read the digital tape and stored the input signals in an array for later use in the simulation and in output. Input to this subroutine consisted of the time on the tape at which the simulation t_o would occur, the time at which grooving was encountered, a parameter to instruct the simulation whether or not to use the pavement grooving function, and the values of the constant parameters in the grooving function.

The second of the new subroutines applied the torque signal to the motorcycle's steering system. One of the revisions made to the programs allowed the taped values of steering torque and steer angle to be printed and plotted, together with the normal output. Another was the inclusion of the TTI pavement grooving function to modify the front and rear tire side forces. This function is as follows:

$$F_{y_{grooved}} = e^{0.638} \alpha^{-0.0116} \gamma^{-0.0124} AA^{0.0308} F_z^{-0.0671} \mu_x^{0.0176} C_\gamma^{0.0874} PF^{-0.2618} F_y^{1.0095}$$

where:

α = Tire slip angle (degrees)

γ = Tire inclination (degrees)

AA = Groove approach angle (degrees)

F_z = Tire normal force (lbs.)

μ_x = Maximum normalized camber thrust (lbs./lbs.)

C_γ = Normalized camber coefficient lbs./(degrees)(lbs.)

PF = Pavement factor

F_y = Ungrooved tire side force (lbs.)

During all runs made in this study, the following parameters in the above equation were held constant:

Approach Angle		1.0 degree
μ_x max (camber)	front	0.7
	rear	0.7
Camber Coefficient	front	0.02 lbs./(degrees)(lbs.)
	rear	0.01 lbs./(degrees)(lbs.)
Pavement Factor		0.75

The simulated motorcycle was upright and at steady state at the beginning of each simulation run, with the values of the state variables and their derivatives set equal to zero*. The taped torque input was then applied and the motorcycle allowed to respond to the torque with no rider control inputs. The time histories of 31 different parameters were printed out for each simulation run. In addition to the printed output, time history plots of several important parameters were made. These parameters and their titles on the plots are: the input steer torque from the tape (STR TORQ), the experimental value of steer angle from the tape (STR(EXP)), the simulated steer angle (STR(SIM)), the simulated roll angle (ROLL), and the simulated yaw angle (YAW). The plots for all the simulated runs are given in Appendix F. Table 10 summarizes the run conditions for the simulation runs made during the study.

The results of the study are rather inconclusive. Because the only parameter available for comparing simulated and experimental results is the steer angle, no firm conclusions can be reached as to how well this method of simulating grooved pavement response on the computer compares with full scale test results. It is noted, however, that the agreement between simulated and experimental steer responses is not particularly good for any of the simulation runs. No actual oscillations of the motorcycle that could be termed weave or wobble were noted, either in the simulated or experimental steering time histories.

*Except for initial forward velocity, which was 70 miles per hour for all runs.

TABLE 10 COMPUTER STUDY RUN CONDITIONS

Run No.	Tape No.	File No.	Tire Press (psi)	Steer Damper	Tape Start Time at Simulation (sec)	Simulation Run Time (sec)	Simulation Time at Start of Grooving (sec)	Grooving Function Used	Motorcycle Configuration
1	ZZ3340	2	12	OUT	6.005	4.5	0.670	YES	STANDARD
2	ZZ3340	1	12	IN	7.651	4.5	0.660	YES	STANDARD
3	ZZ3340	2	12	OUT	6.005	4.5	0.670	YES	ZERO STEER DAMPING
4	ZZ3341	1	22	OUT	3.642	4.8	2.241	YES	ZERO STEER DAMPING
5	ZZ3340	1	12	IN	4.015	4.8	4.296	YES	STANDARD
6	ZZ3575	3	12	OUT	2.010	4.8	2.256	YES*	STANDARD
7	ZZ3575	4	12	OUT	6.305	4.8	2.256	YES*	ZERO STEER DAMPING
8	ZZ3575	3	12	IN	2.010	4.8	2.256	NO	STANDARD
9	ZZ3340	2	12	OUT	6.005	4.8	0.670	NO	STANDARD
10	ZZ3575	5	22	OUT	0.000	4.8	1.875	YES	STANDARD
11	ZZ3575	5	22	OUT	0.000	4.8	1.875	NO	STANDARD
12	ZZ3575	3	12	IN	2.010	4.8	2.256	YES	STANDARD
13	ZZ3575	4	12	OUT	6.311	4.8	2.250	YES	STANDARD
14	ZZ3575	4	12	OUT	6.311	4.8	2.250	NO	STANDARD

*In these runs, probable errors in the event channel of tape ZZ3575 caused the grooving function not to start at the same time the motorcycle encountered the grooved pavement.

The lack of correlation between simulation and experiment for Runs 1-5 led to the theory that the high frequency content of the torque signal was masking the frequencies tending to induce an oscillation in the motorcycle. As an attempt to correct this condition, the data was low-pass filtered with a 30 Hz cutoff frequency to produce tape ZZ3575. This tape contained the same data as the previous two unfiltered tapes (ZZ3340 and ZZ3341). The results using the filtered data produced much the same results as the unfiltered data.

One conclusion that can be reached is the effect of the grooving function on the motorcycle response. The run conditions for runs 1 and 9, 8 and 12, 10 and 11, and 13 and 14 are identical except for the use of the grooving function. Comparison of the plotted results from these runs shows virtually identical responses. It can be concluded therefore that the grooving power law has very little effect on motorcycle response under the conditions used in this study.

It is evident that more work is needed to study the influence of pavement grooving on motorcycle handling, especially since handling differences are noted by test riders; the limited resources of this program were not equal to the task of providing a satisfactory solution to this problem.

APPENDIX F

MOTORCYCLE SIMULATION DESCRIPTION AND PLOTTED RESULTS OF SIMULATION STUDY

In this appendix, the characteristics of Calspan's motorcycle simulation program are discussed in general terms to demonstrate its capability to treat various operating conditions and control modes. The description of the mathematical model on which it is based is quite brief; it is described in more detail in Reference 16.

The vehicle-rider model is a system of three rigid masses with eight degrees of freedom of motion: six rigid-body degrees of freedom of the rear frame, a steer degree of freedom of the front wheel, and a rider lean degree of freedom (see Figure 41). The basic physical parameters of the vehicle which are included in the mathematical analysis are shown in Figure 42, where θ_F is the rake angle of the steer axis and δ is the steer angle of the front wheel about the inclined steer axis. The symbols M_D, M_R, M_F represent the masses of the rider, the rear wheel and frame, and the front wheel and steering fork assembly, respectively.

The analysis is based on the following assumptions:

(1) The mass distribution of the vehicle is assumed to be symmetrical with respect to the vertical-longitudinal plane through the geometrical center of the vehicle. Thus, the X-Y and Y-Z products of inertia are assumed to be zero. X-Z products of inertia and all moments of inertia of each rigid mass are included.

(2) The vehicle is assumed to be moving through still air on a flat level surface. The aerodynamic drag, the front to rear weight transfer due to aerodynamic drag, and the pitching moment, aerodynamic lift, and steer moment due to windshield aerodynamic drag are included as approximations.

(3) A driving thrust on the rear wheel is included to overcome the aerodynamic drag. Thus, the vehicle is initially moving at constant speed. Front tire rolling resistance is assumed negligible.

(4) Tire lateral forces as functions of slip angle, inclination (camber) angle, and vertical load are modeled independently for front and rear tires.

(5) External torques acting about the steer axis include the moments due to the lateral and vertical tire forces, tire aliging torque, and a

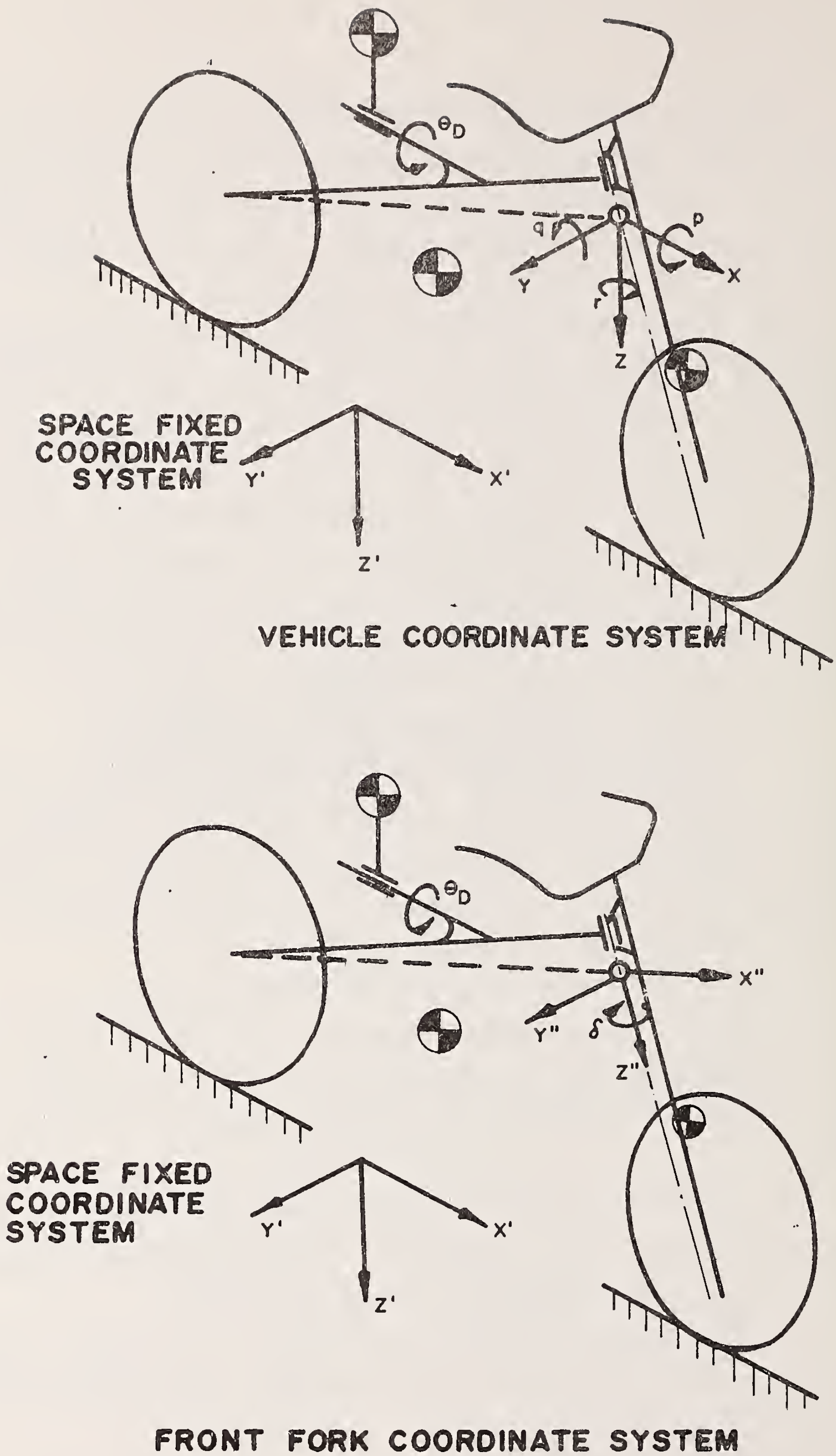


FIGURE 41 - TWO - WHEEL VEHICLE MODEL.

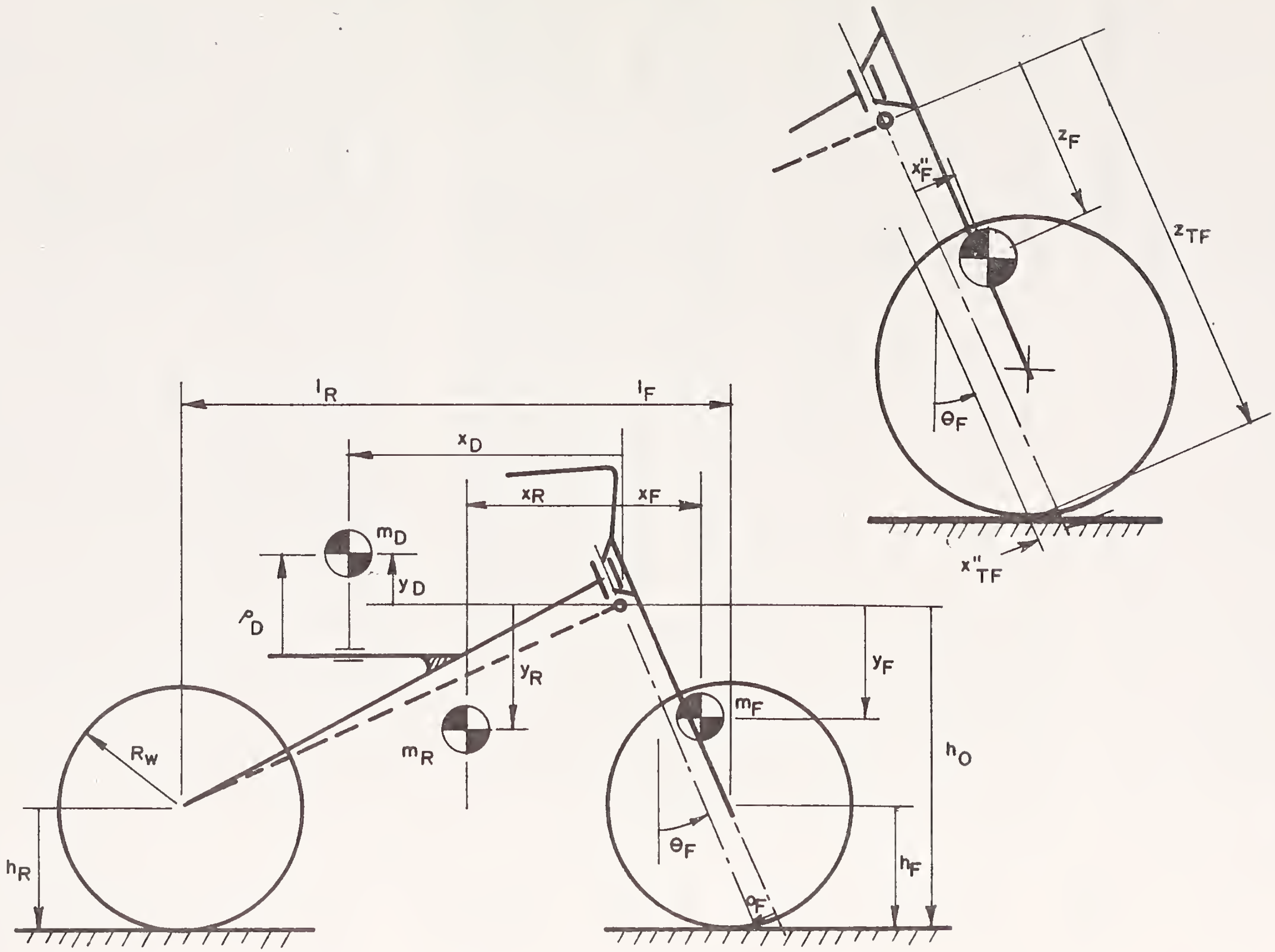


FIGURE 42-CHARACTERISTIC DIMENSIONS OF MOTORCYCLE MODEL.

couple due to the aerodynamic drag force on the windshield. The gyroscopic moments of the wheels and engine are included.

(6) Viscous steering damping is included between the front assembly and the rear frame.

(7) The axis of rotation of the engine is assumed to be transverse with the direction of rotation of the engine the same as that of the wheels.

To analyze the handling of a two-wheel vehicle in the nonlinear region of operation, the equations of motion are written in complete nonlinear form. All inertial coupling terms between the rider, the front assembly, and the rear frame are included. The digital computer simulation program for this analysis solves the equations of motion for prescribed rider control inputs and/or disturbance inputs and produces time histories of the resultant vehicle motions.

The simulation program, consisting of twelve subroutines, uses approximately 200 K bytes of core storage when run on an IBM System/370 Model 165 computer. The output processor program uses approximately 160K bytes of core storage.

Over one hundred input variables are required by the simulation program. These data include forty-six vehicle parameters: dimensions, weights, moments of inertia, tire side force coefficients, aerodynamic coefficients, etc.

The digital computer simulation program consists basically of the application of a modified Runge-Kutta step-by-step procedure to integrate the equations of motion. The integration step size is a variable although a value of 0.01 second is generally used. The solution of up to 10 seconds of simulated real time may be obtained with a step size of 0.01 second. Solution output is obtained from a separate output processor program which can produce time histories of as many as 36 variables (translational and angular positions, velocities, accelerations, tire force components, etc.) in both printed and plotted format.

MOTORCYCLE DYNAMICS COMPUTER SIMULATION INPUT FORM

IDENTIFICATION FIELDS:*

YAMAHA RD 350

BASELINE DATA SET

1. GENERAL VEHICLE PARAMETERS:

Wheelbase (in)	52.0
Total Weight (lb)	352.0
Portion of Total Motorcycle Weight on the Front Wheel (Percent)	45.0
Location of Total C.G. Above Ground (in)	18.0
Total Roll Moment of Inertia About Axis Through Total C.G. (lb-in-sec^2)	80.0
Total Pitch Moment of Inertia About Axis Through Total C.G. (lb-in-sec^2)	280.0
Total Yaw Moment of Inertia About Axis Through Total C.G. (lb-in-sec^2)	255.0
Total Roll-Yaw Product of Inertia About Axis Through Total C.G. (lb-in-sec^2)	0.0
Weight of Front Fork Assembly (Fork, Wheel, Handlebars, Windshield) (lb)	65.0
Perpendicular Distance From C.G. of Front Fork Assembly to Steer Axis (in)	2.6

*These two cards must be included in every data set (even if blank). They make available a total of 144 columns for identification of vehicle configuration, run no., etc., at user's discretion. The information entered will appear at the top of each sheet of computer printout and at the top of each plot.

Distance Parallel to Steer Axis From C.G. of Front Fork Assembly to Front Wheel Center (in)	12.5
Roll Moment of Inertia of Front Fork Assembly About an Axis Perpendicular to the Steer Axis Through C.G. of Assembly ($lb\text{-}in\text{-}sec^2$)	34.0
Pitch Moment of Inertia of Front Fork Assembly About an Axis Perpendicular to the Steer Axis Through C.G. of Assembly ($lb\text{-}in\text{-}sec^2$)	36.0
Yaw Moments of Inertia of Front Fork Assembly About the Steer Axis ($lb\text{-}in\text{-}sec^2$)	5.5
Roll-Yaw Product of Inertia of Front Fork Assembly About an Axis Through the C.G. of the Assembly ($lb\text{-}in\text{-}sec^2$)	0.0

2. RIDER PARAMETERS:

a. Standard Rider Model:	--
Weight of Rider (lb)	--
Portion of Rider Weight on Front Wheel (percent)	--
Height of Rider C.G. Above Ground (in)	--
Height of Saddle Above Ground (in)	--
Roll Moment of Inertia of Rider About an Axis Through His C.G. ($lb\text{-}in\text{-}sec^2$)	--
Pitch Moment of Inertia of Rider About an Axis Through His C.G. ($lb\text{-}in\text{-}sec^2$)	--
Yaw Moment of Inertia of Rider About an Axis Through His C.G. ($lb\text{-}in\text{-}sec^2$)	--
Roll-Yaw Product of Inertia of Rider About an Axis Through His C.G. ($lb\text{-}in\text{-}sec^2$)	--

b. Alternate Rider Model

Height of Rider (in)	72.0
Weight of Rider (lb)	200.0
Height of Saddle Above Ground (in)	31.0
Location of Saddle Forward of Rear Wheel ℄(in)	9.0
Height of Foot Pegs Above Ground (in)	12.0
Location of Foot Pegs Forward of Rear Wheel ℄(in)	21.0
Height of Handgrips Above Ground (in)	40.0
Location of Handgrips Forward of Rear Wheel ℄(in)	31.0

3. FRONT FORK PARAMETERS:

Caster Angle of the Steer Axis (deg)	27.5
Nominal Steering Trail (in)	3.7
Front Tire Pneumatic Trail (in)	0.8
Steering Viscous Damping Coefficient (in-lb/deg/sec)	0.5
Steering Hydraulic Damping Coefficient (in-lb/deg^2/sec^2)	0.0
Spin Moment of Inertia of Front Wheel (lb-in-sec^2)	4.0
Spin Moment of Inertia of Rear Wheel (lb-in-sec^2)	8.0
Front Tire Lateral Force Runout (lb)	0.0

4. AERODYNAMICS PARAMETERS:

Aerodynamic Drag Coefficient (dimensionless)	--
Aerodynamic Lift Coefficient (dimensionless)	--
Total Frontal Area (in^2)	--
Lateral Offset of C.P. From Motorcycle ℄ (in)	--
Height of Center of Pressure Above Ground (in)	--
Aerodynamic Drag Coef. of Windshield (dimensionless)	--
Frontal Area of Windshield (in)	--
Location of Windshield C.P. Forward of Steer Axis (in)	--

7. PATH INPUT DATA:

Number of Path Segments	--
X and Y Coordinates of Path Segment Junction Points	--

(The Number of Sets of Coordinates Must Be One Greater Than the Number of Path Segments)

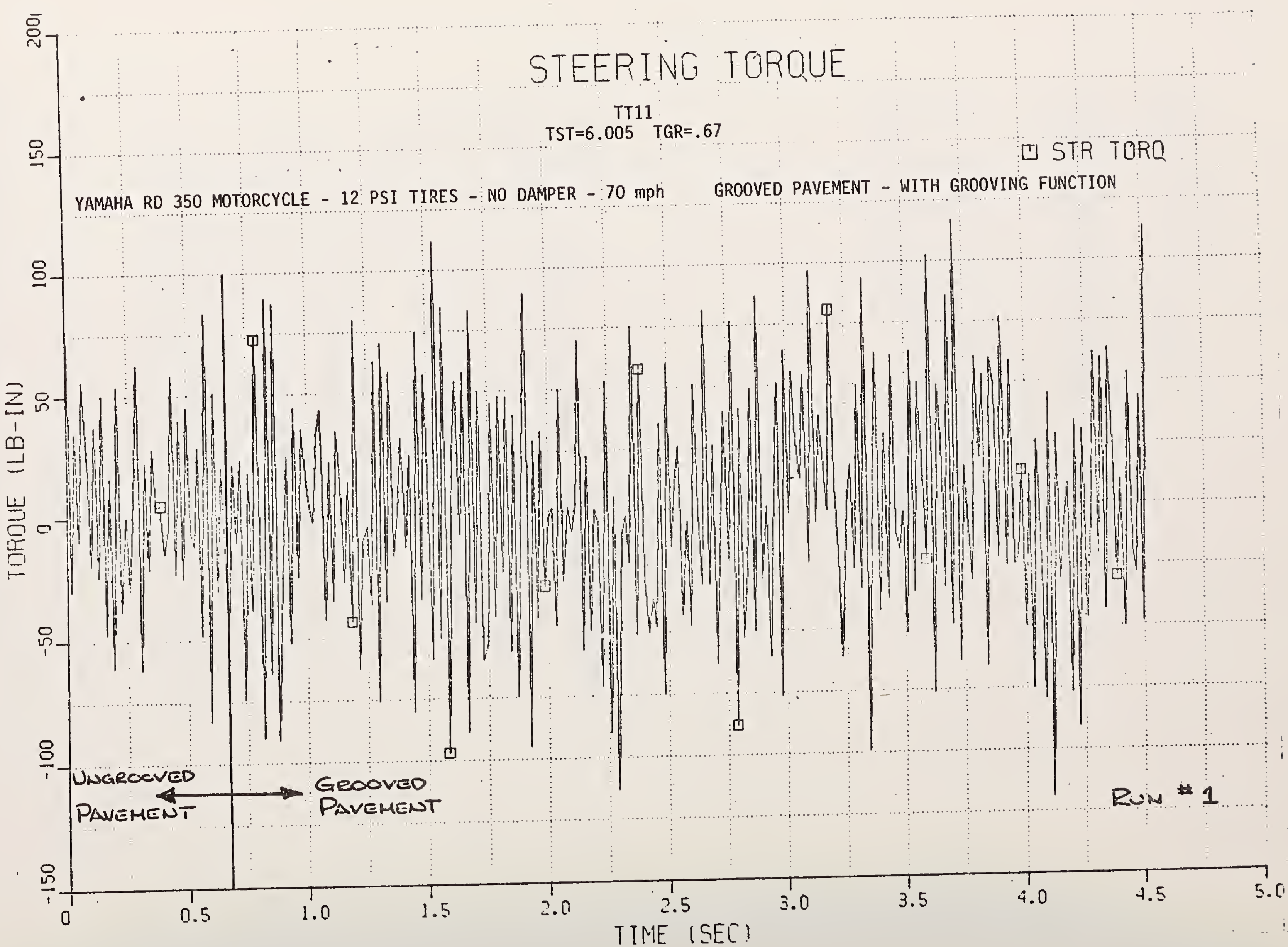
8. TIRE PARAMETERS:

	FRONT	REAR
Undeflected Tire Rolling Radius (in)	12.5	12.6
Tire Section Width (in)	3.00	3.50
Radial Stiffness of Tire (lb/in)	600.0	850.0
Radial Damping Coefficient of Tire (lb/in/sec)	0.0	0.0
Slip Angle-Tire Side Force Coefficient (lb/(lb/deg))	0.3	0.24
Slip Angle Cubed - Tire Side Force Coefficient (lb/(lb/deg^3))	-0.001	-0.0008
Inclination Angle - Tire Side Force Coefficient (lb/(lb/deg))	0.02	0.01
Tire Relaxation Length (in)	0.0	0.0

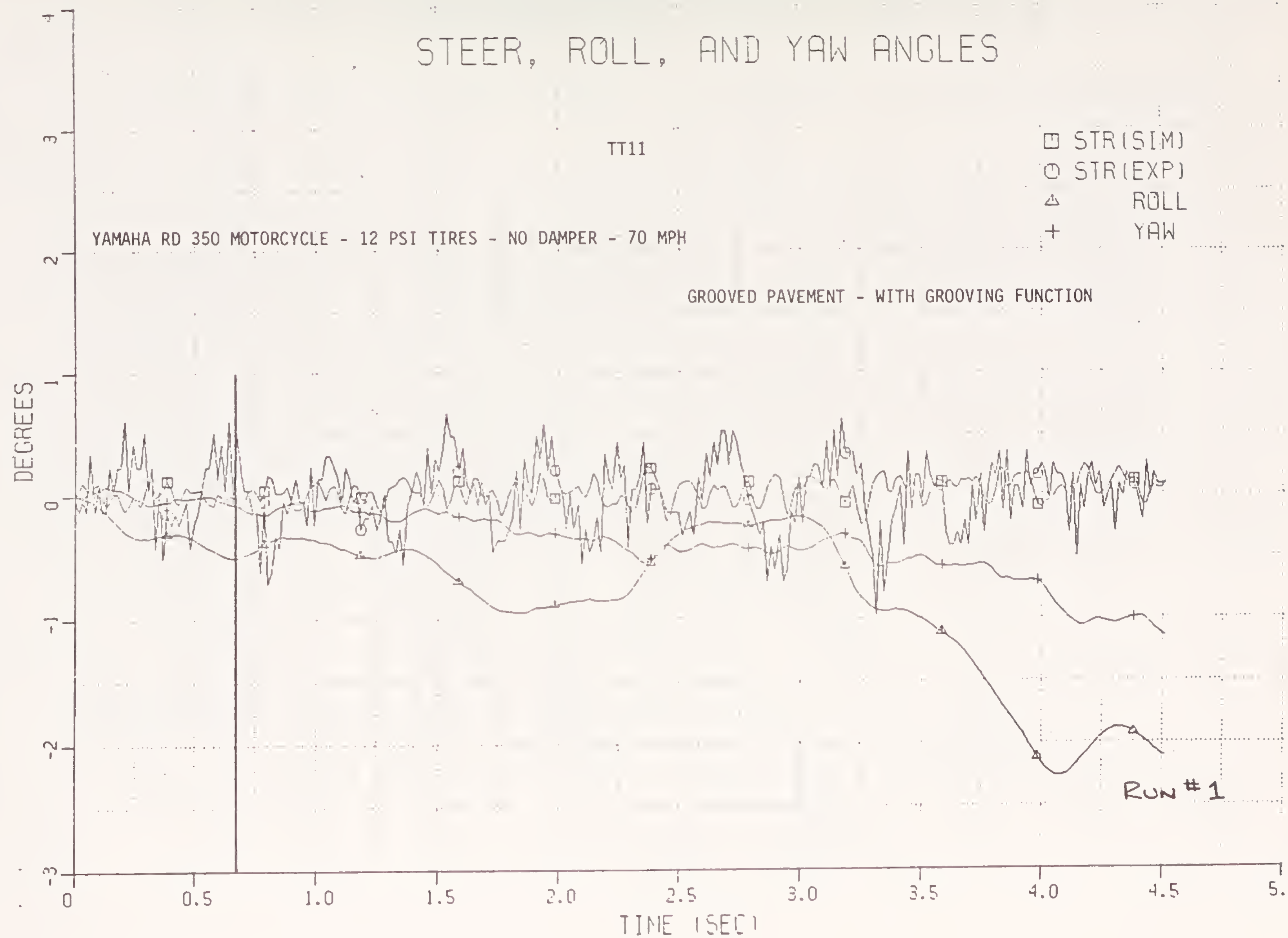
END OF VEHICLE INPUT DATA* 9999

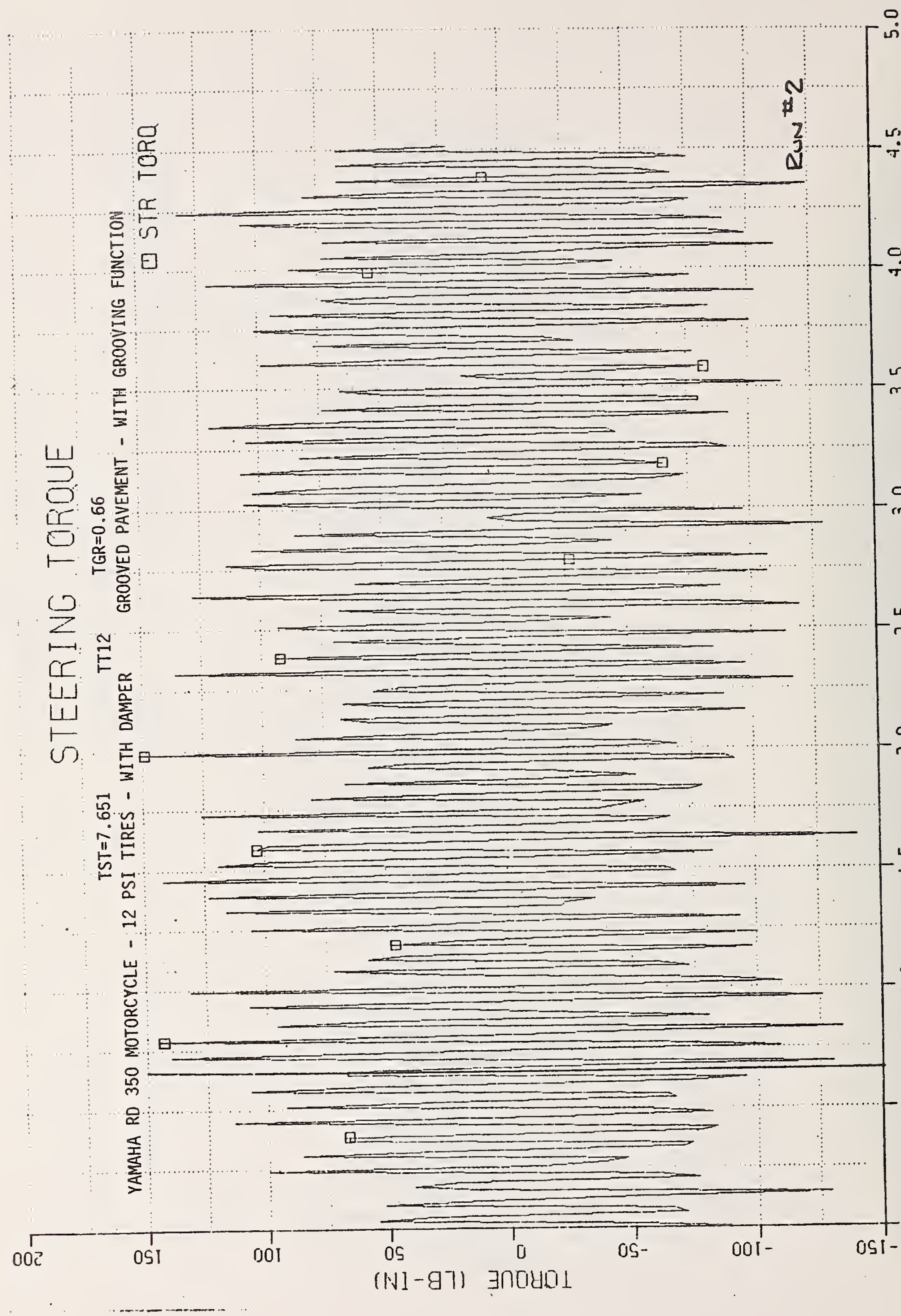
*This card must be included in every data set.

PLOTTED RESULTS OF SIMULATION STUDY

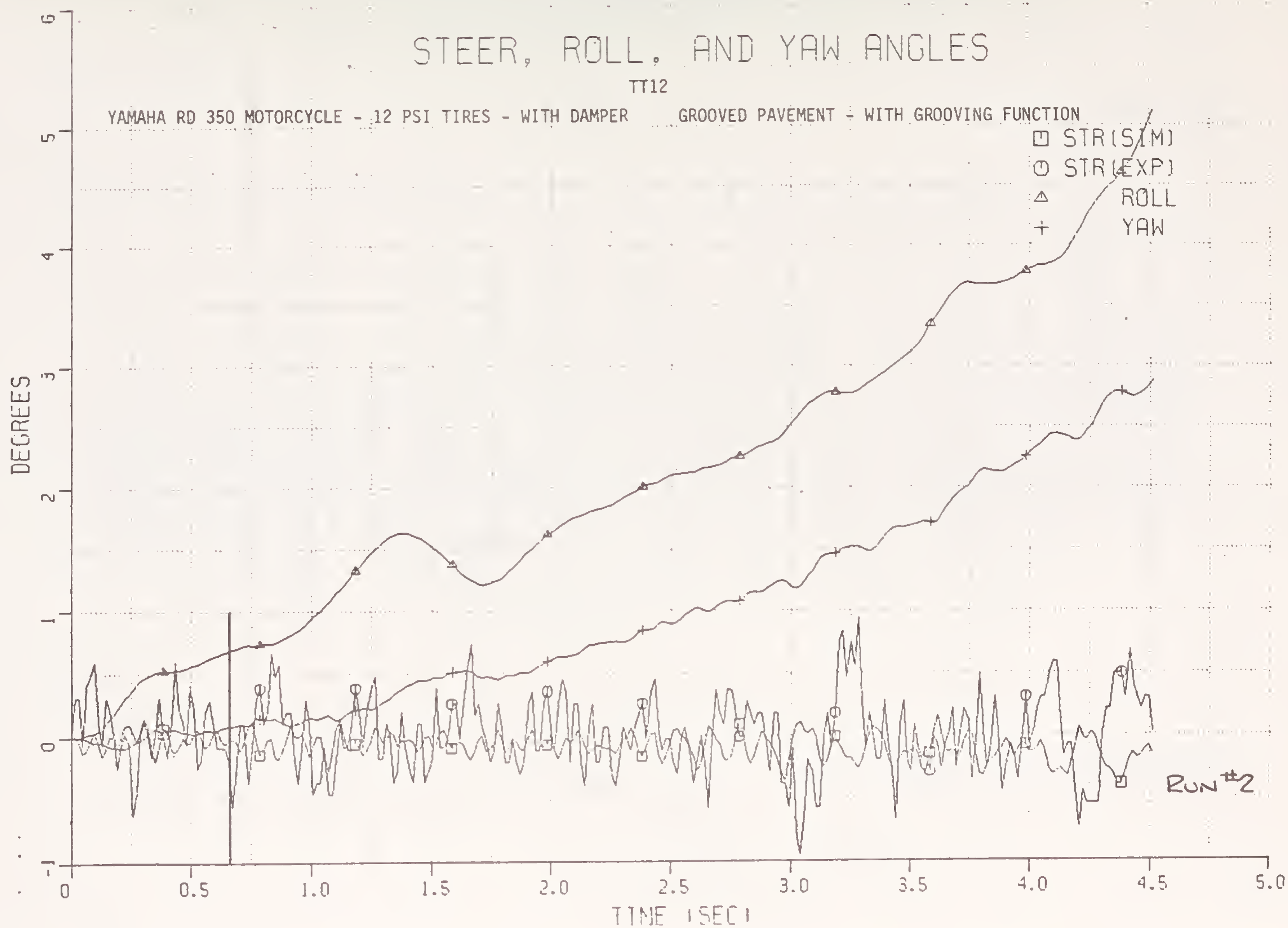


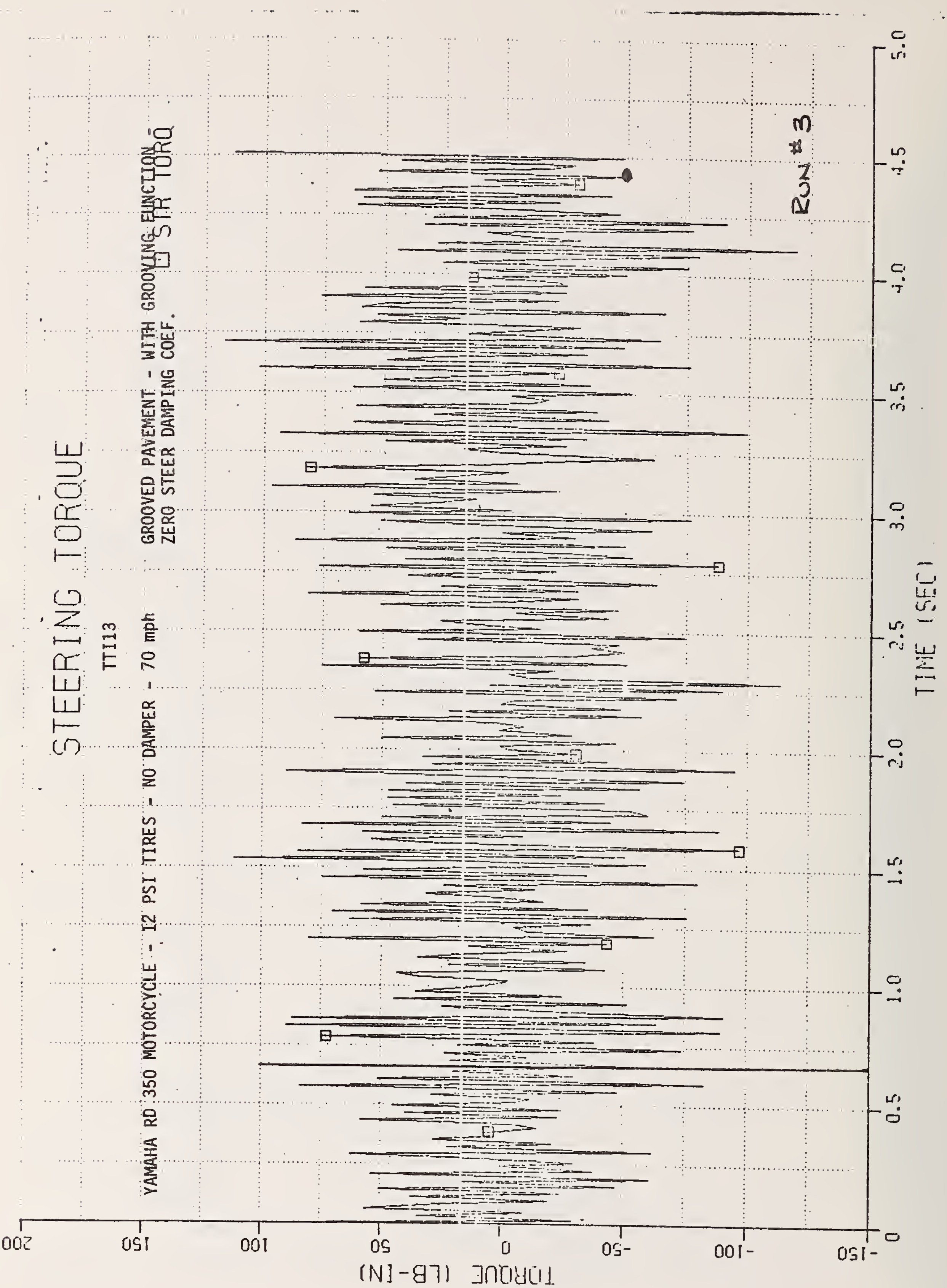
STEERING TORQUE
TT11
TST=6.005 TGR=.67
STR TORQ
YAMAHA RD 350 MOTORCYCLE - 12 PSI TIRES - NO DAMPER - 70 mph
GROOVED PAVEMENT - WITH GROOVING FUNCTION
TORQUE (LB-IN)
200
150
100
50
0
-50
-100
-150
TIME (SEC)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
UNGROOVED PAVEMENT
GROOVED PAVEMENT
RUN # 1

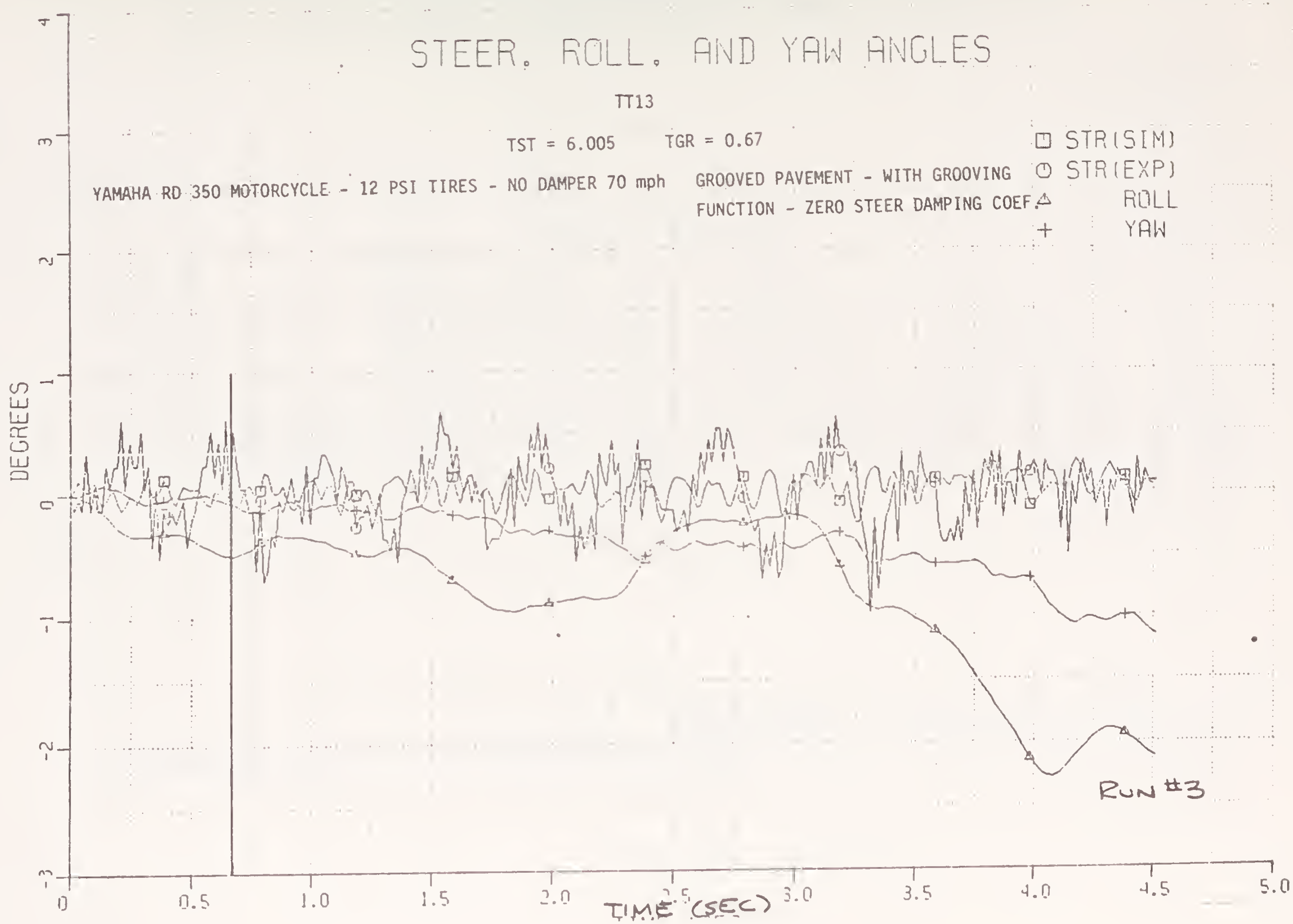

STEER, ROLL, AND YAW ANGLES
TT11
YAMAHA RD 350 MOTORCYCLE - 12 PSI TIRES - NO DAMPER - 70 MPH
GROOVED PAVEMENT - WITH GROOVING FUNCTION
STR(SIM)
STR(EXP)
ROLL
YAW
DEGREES
TIME (SEC)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
4
3
2
1
0
-1
-2
-3
RUN #1

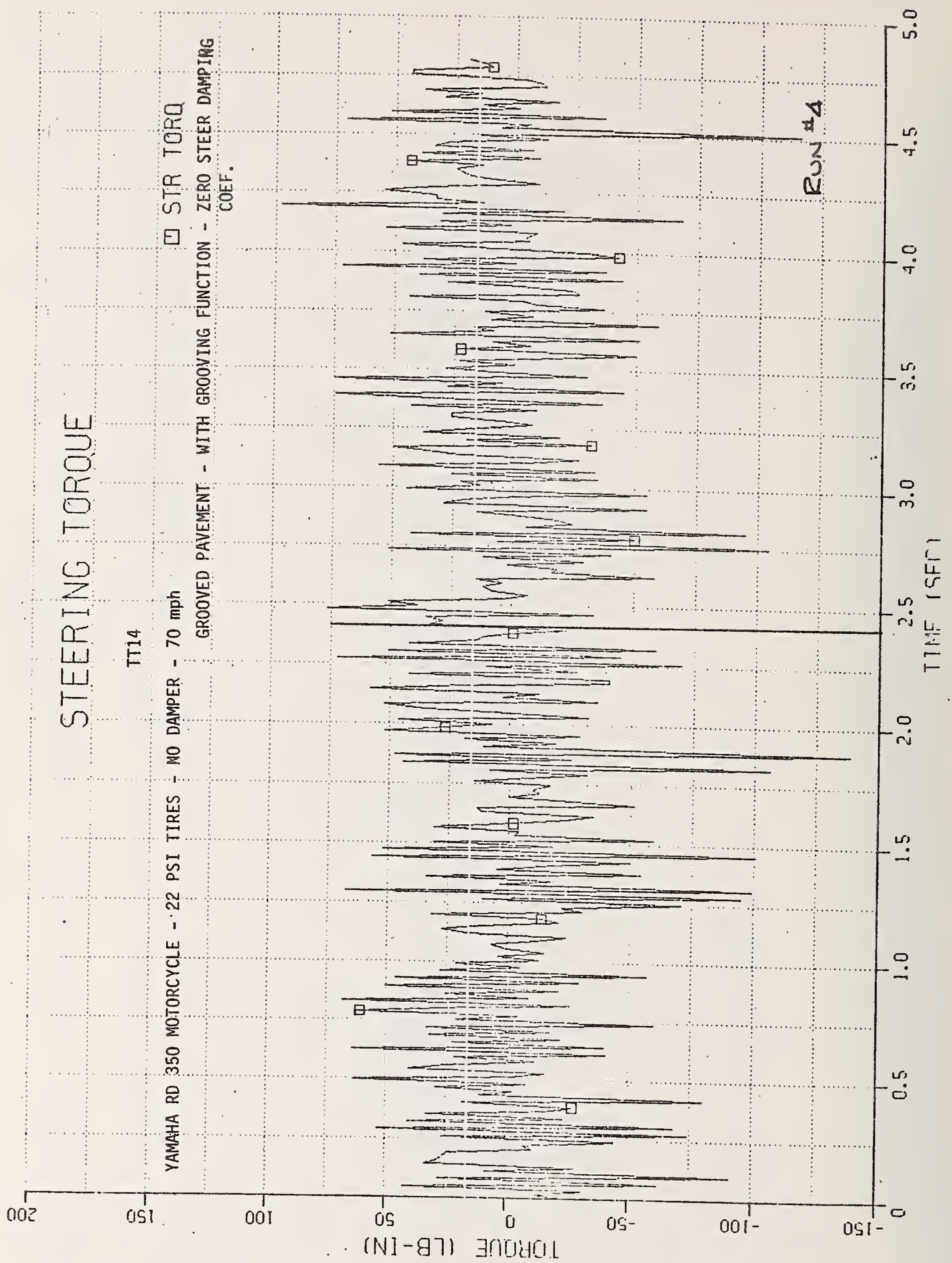


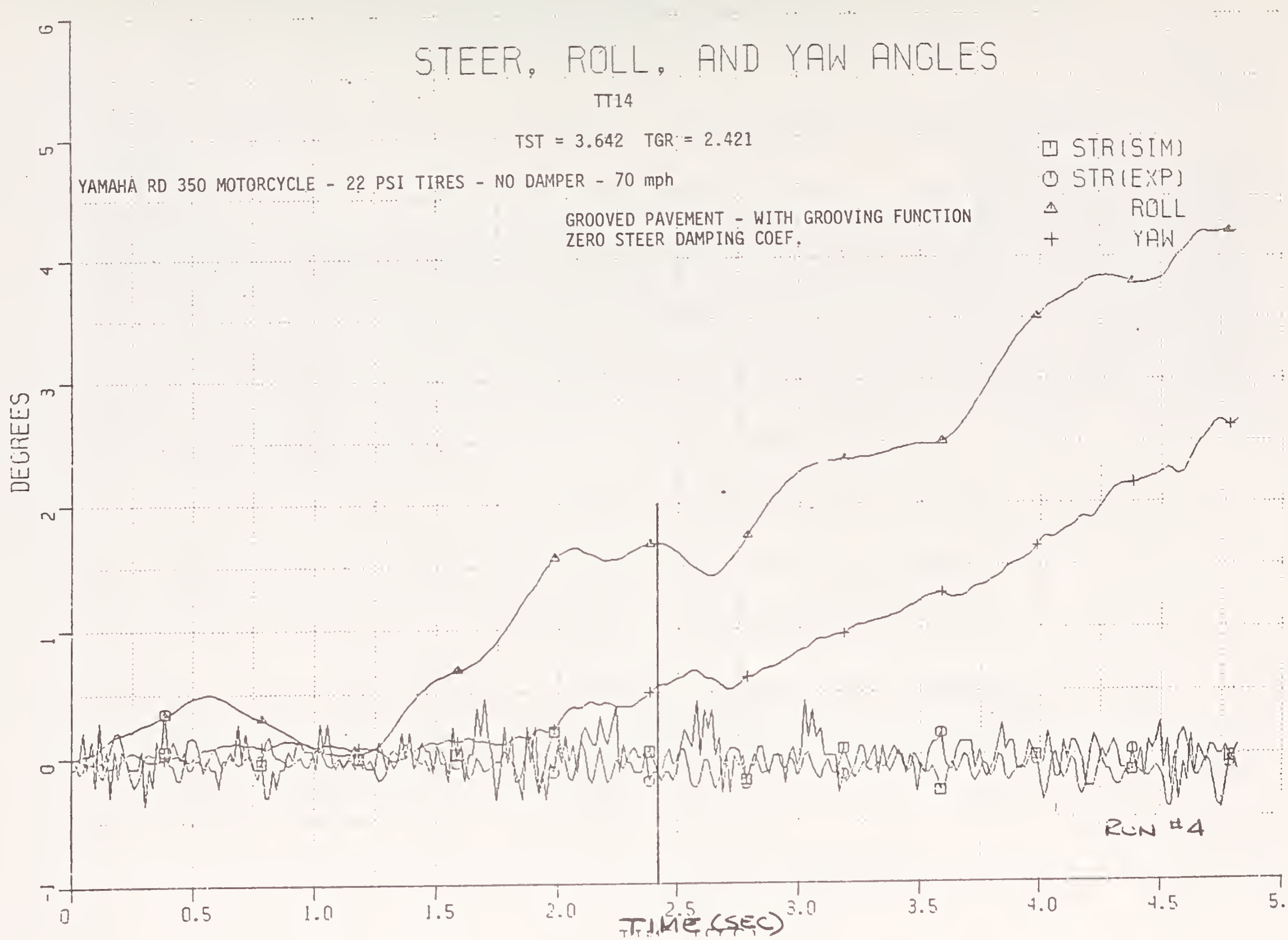
STEERING TORQUE
TST=7.651 TT12 TGR=0.66
YAMAHA RD 350 MOTORCYCLE - 12 PSI TIRES - WITH DAMPER GROOVED PAVEMENT - WITH GROOVING FUNCTION
STR TORQ
RUN #2
TORQUE (LB-IN)
-150
-100
-50
0
50
100
150
200
TIME (SEC)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

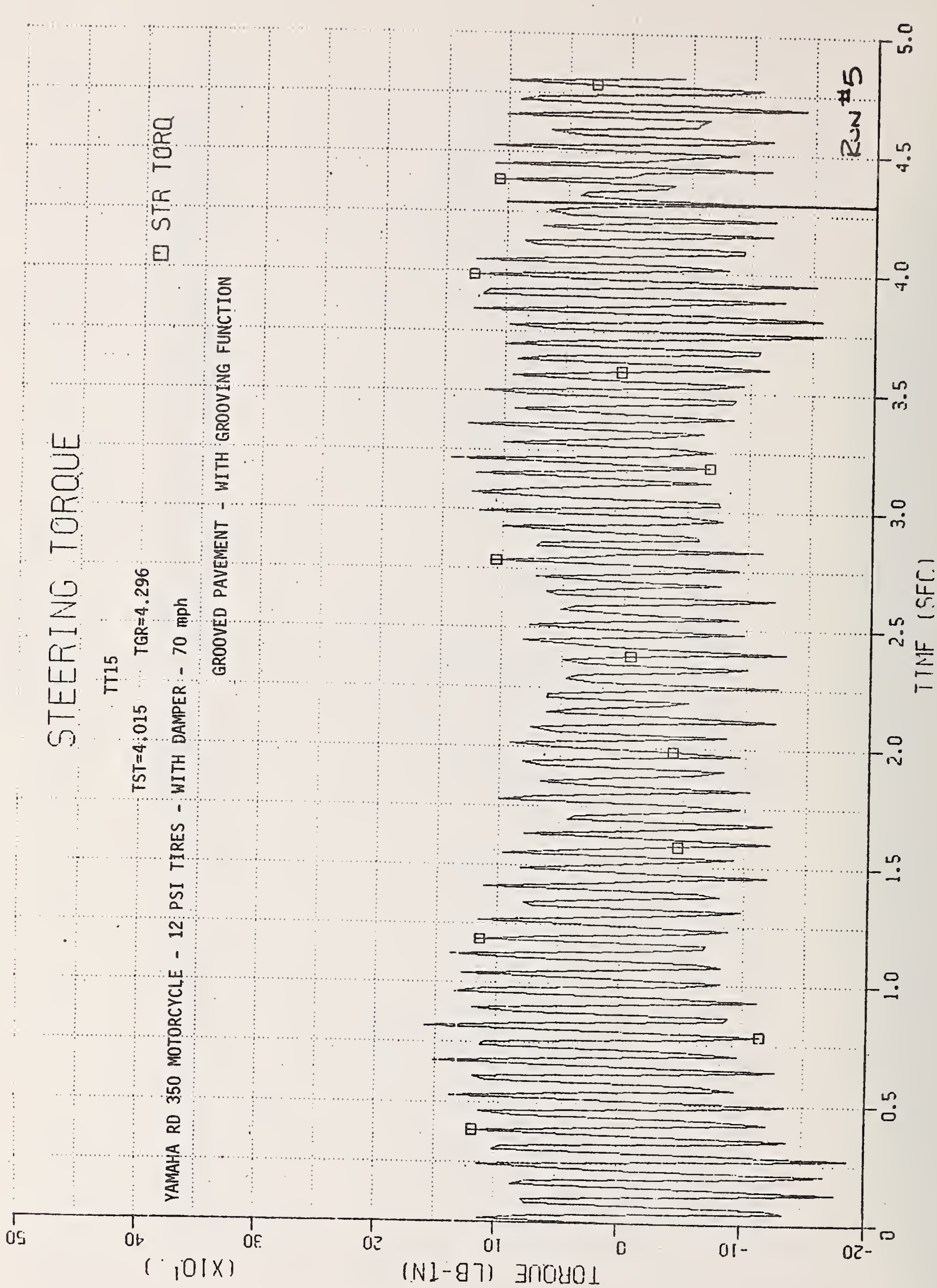

STEER, ROLL, AND YAW ANGLES
TT12
YAMAHA RD 350 MOTORCYCLE - 12 PSI TIRES - WITH DAMPER
GROOVED PAVEMENT - WITH GROOVING FUNCTION
STR(SIM)
STR(EXP)
ROLL
YAW
DEGREES
TIME (SEC)
RUN #2

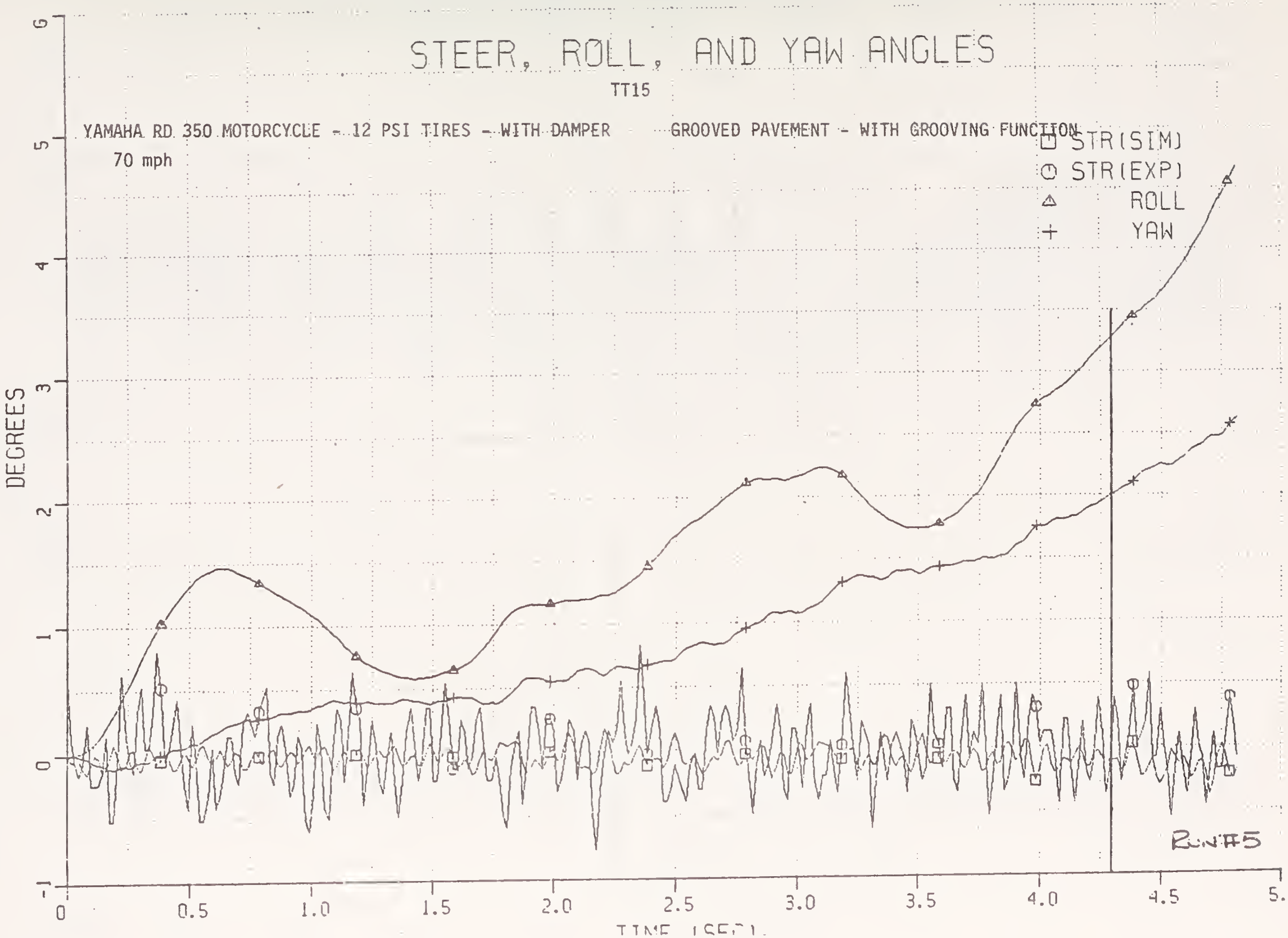

STEERING TORQUE
TTI13
YAMAHA RD 350 MOTORCYCLE - 12 PSI TIRES - NO DAMPER - 70 mph
GROOVED PAVEMENT - WITH GROOVING FUNCTION
ZERO STEER DAMPING COEF.
STR TORQ
RUN # 3
TIME (SEC)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
TORQUE (LB-IN)
200
150
100
50
0
-50
-100
-150

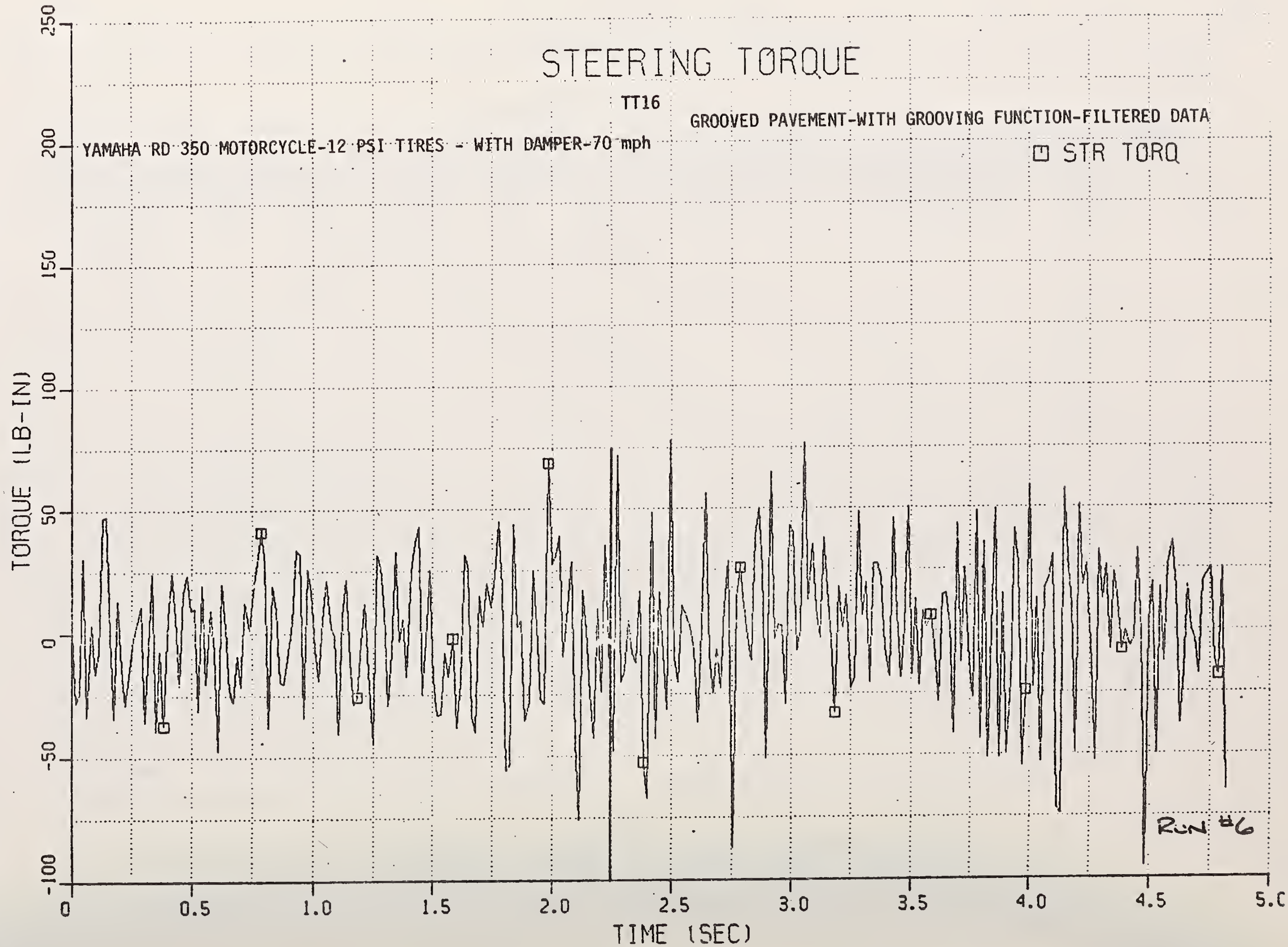

STEER, ROLL, AND YAW ANGLES
TT13
TST = 6.005 TGR = 0.67
YAMAHA RD 350 MOTORCYCLE - 12 PSI TIRES - NO DAMPER 70 mph GROOVED PAVEMENT - WITH GROOVING FUNCTION - ZERO STEER DAMPING COEF.
STR(SIM)
STR(EXP)
ROLL
YAW
DEGREES
TIME (SEC)
RUN #3


STEERING TORQUE
TT14
YAMAHA RD 350 MOTORCYCLE - 22 PSI TIRES - NO DAMPER - 70 mph
GROOVED PAVEMENT - WITH GROOVING FUNCTION - ZERO STEER DAMPING COEF.
STR TORQ
RUN #4
TORQUE (LB-IN)
TIME (SEC)
200
150
100
50
0
-50
-100
-150
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

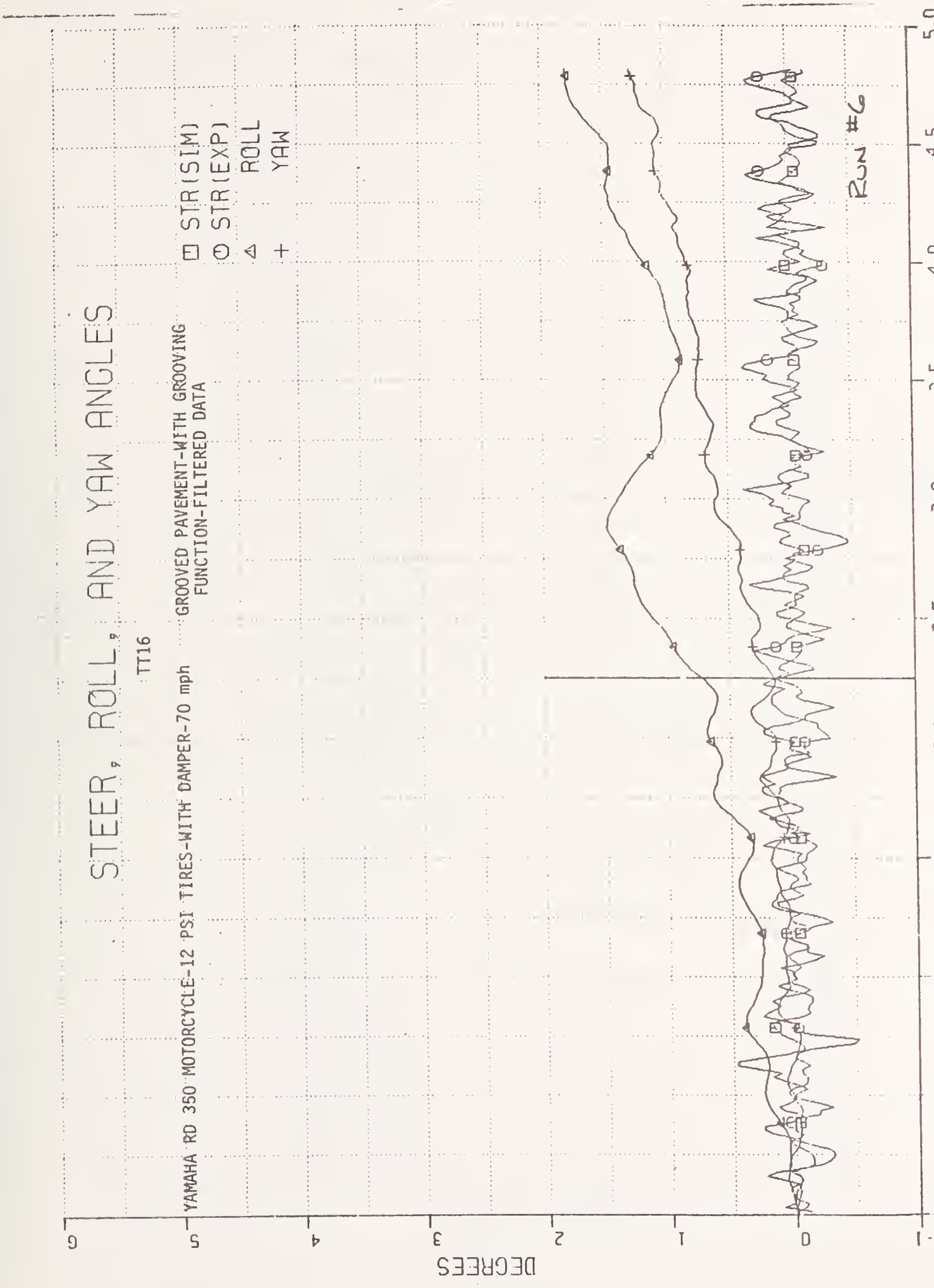

STEER, ROLL, AND YAW ANGLES
TT14
TST = 3.642   TGR = 2.421
YAMAHA RD 350 MOTORCYCLE - 22 PSI TIRES - NO DAMPER - 70 mph
GROOVED PAVEMENT - WITH GROOVING FUNCTION
ZERO STEER DAMPING COEF.
STR(SIM)
STR(EXP)
ROLL
YAW
DEGREES
TIME (SEC)
RUN #4
-1
0
1
2
3
4
5
6
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0


STEERING TORQUE
TT15
TST=4.015 TGR=4.296
YAMAHA RD 350 MOTORCYCLE - 12 PSI TIRES - WITH DAMPER - 70 mph
GROOVED PAVEMENT - WITH GROOVING FUNCTION
STR TORQ
RUN #5
TORQUE (LB-IN) (X10¹)
50
40
30
20
10
0
-10
-20
TIME (SEC)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

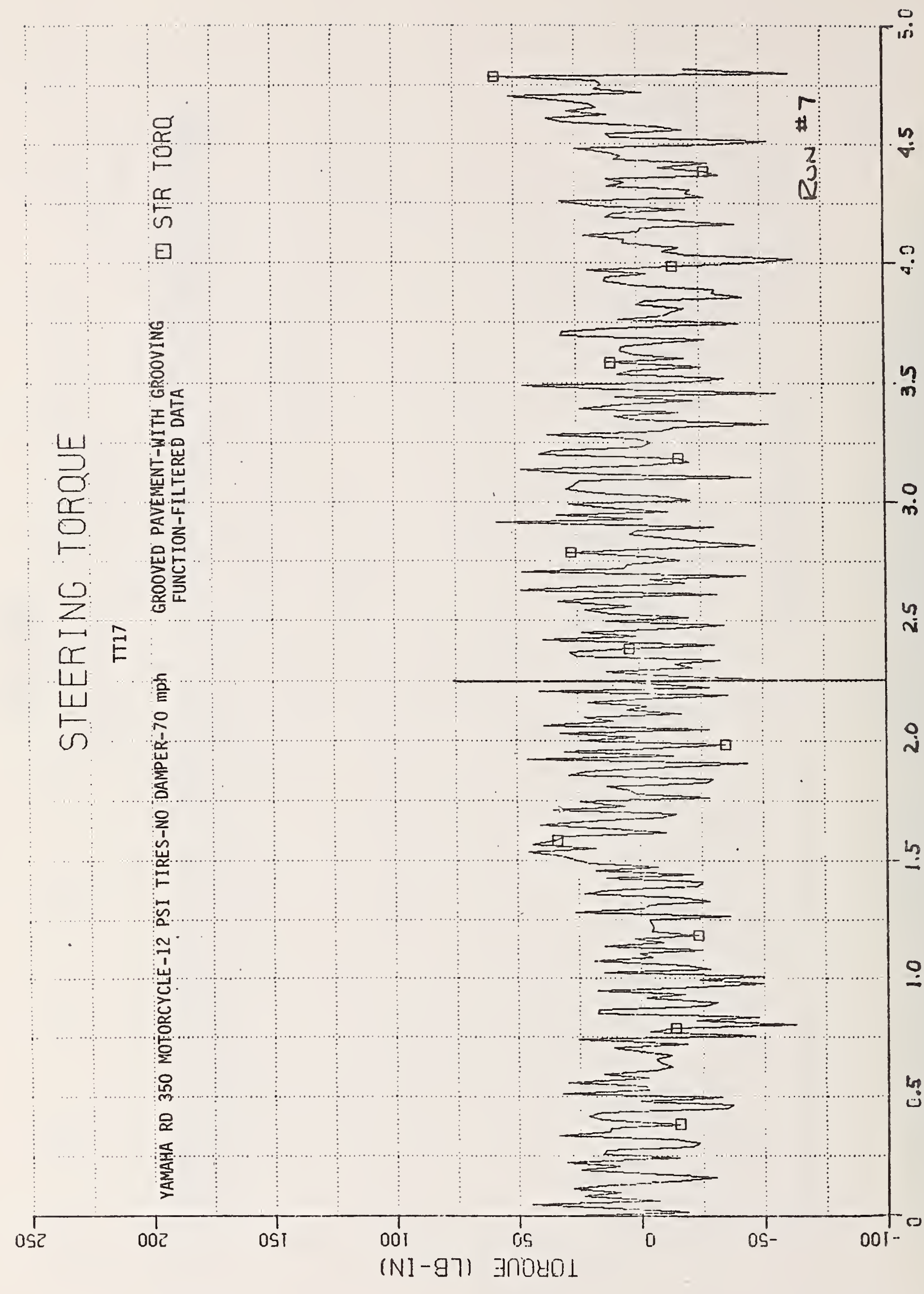

STEER, ROLL, AND YAW ANGLES
TT15
YAMAHA RD 350 MOTORCYCLE - 12 PSI TIRES - WITH DAMPER
70 mph
GROOVED PAVEMENT - WITH GROOVING FUNCTION
STR(SIM)
STR(EXP)
ROLL
YAW
DEGREES
6
5
4
3
2
1
0
-1
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Run #5

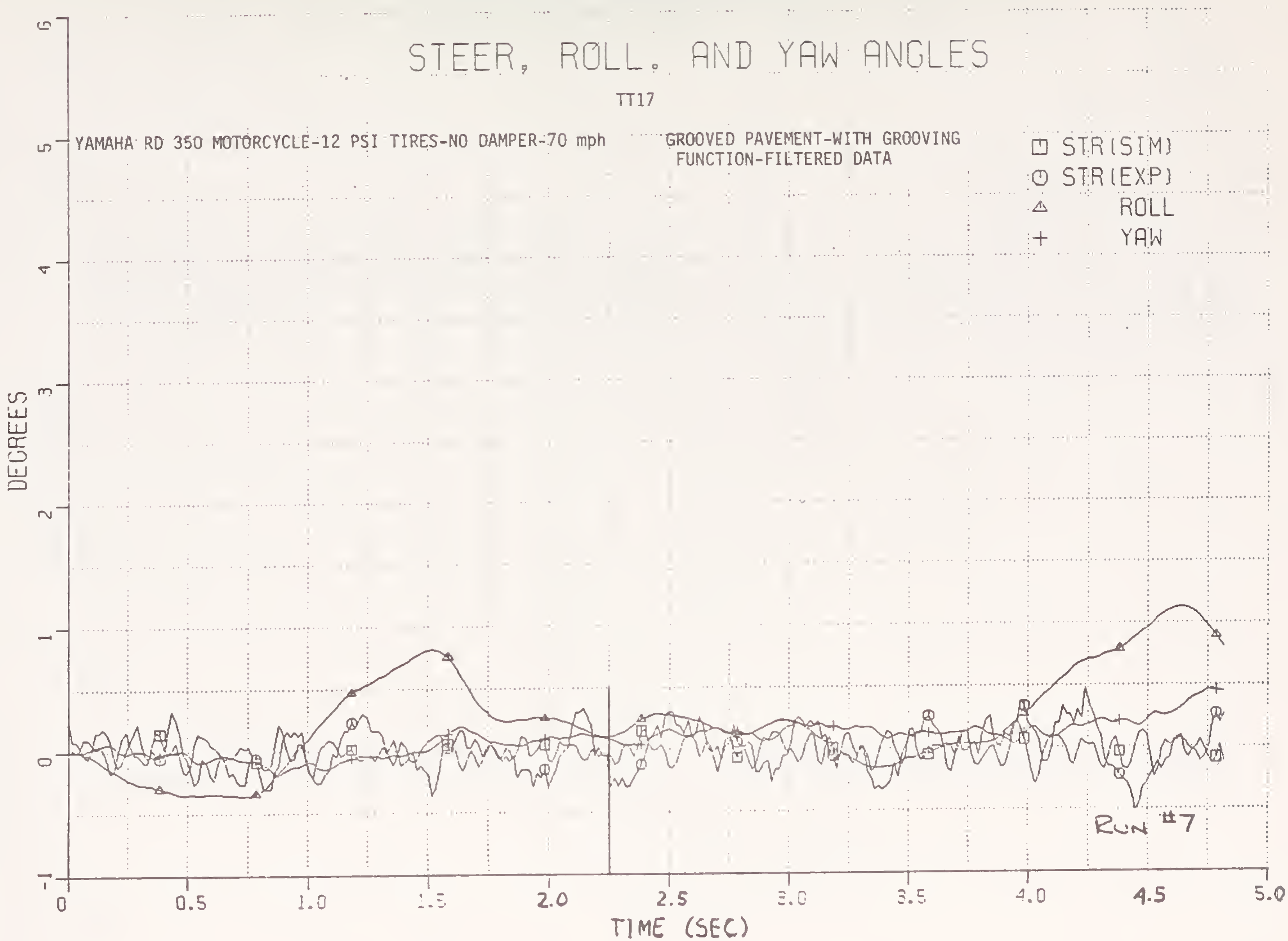


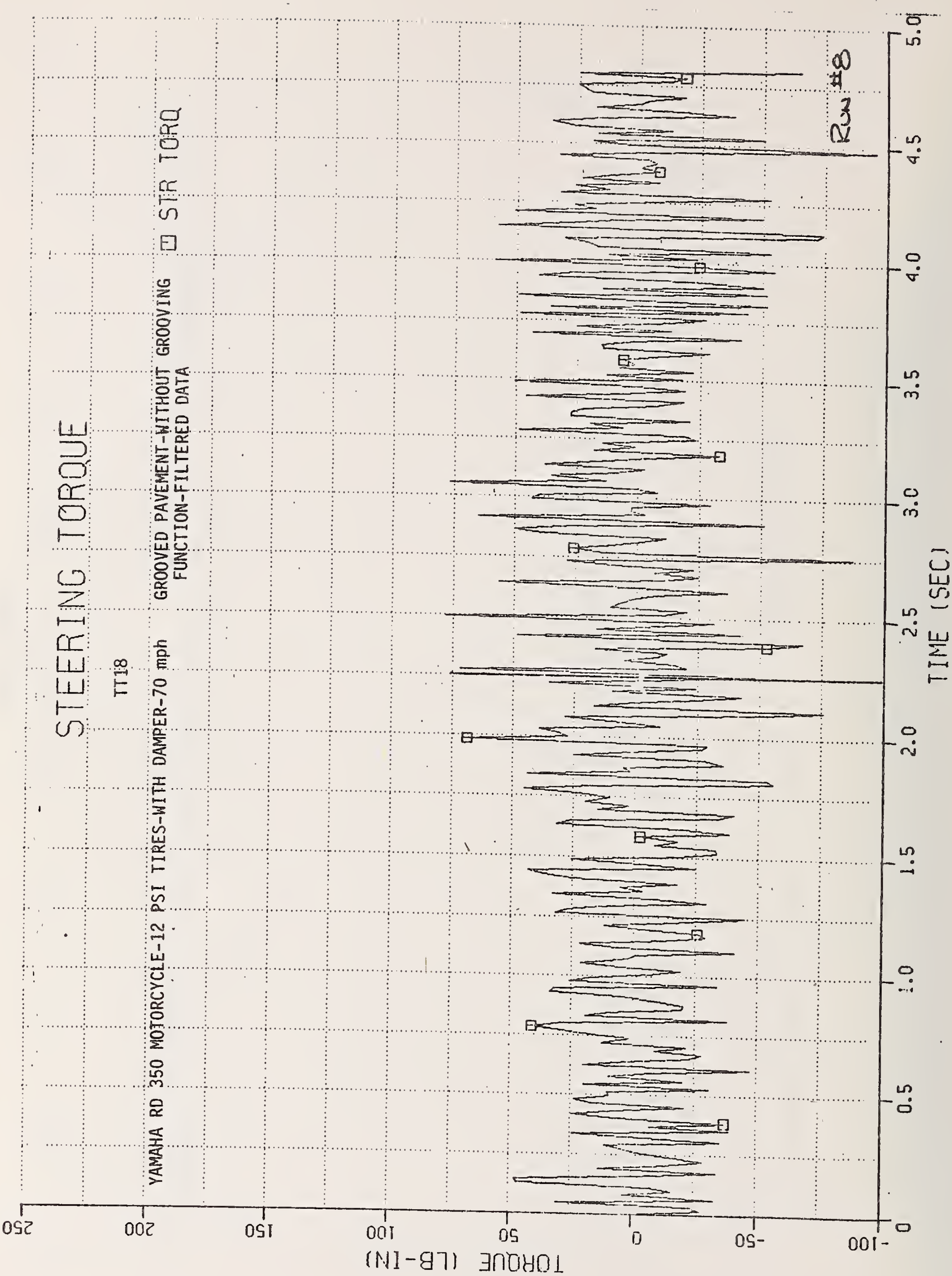
STEERING TØRQUE
TT16
GROOVED PAVEMENT-WITH GROOVING FUNCTION-FILTERED DATA
YAMAHA RD 350 MOTORCYCLE-12 PSI TIRES - WITH DAMPER-70 mph
STR TØRQ
TØRQUE (LB-IN)
TIME (SEC)
RUN #6

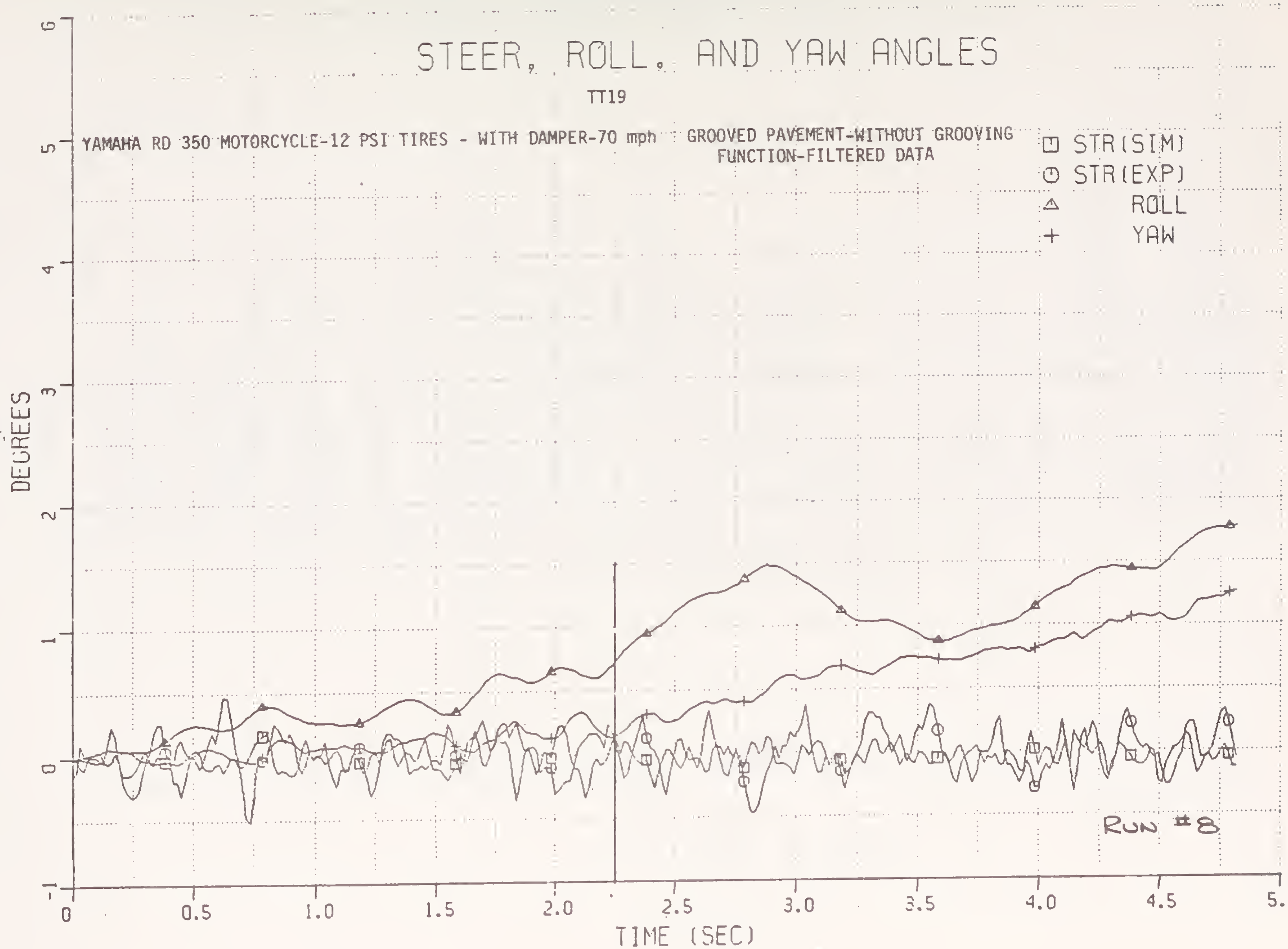


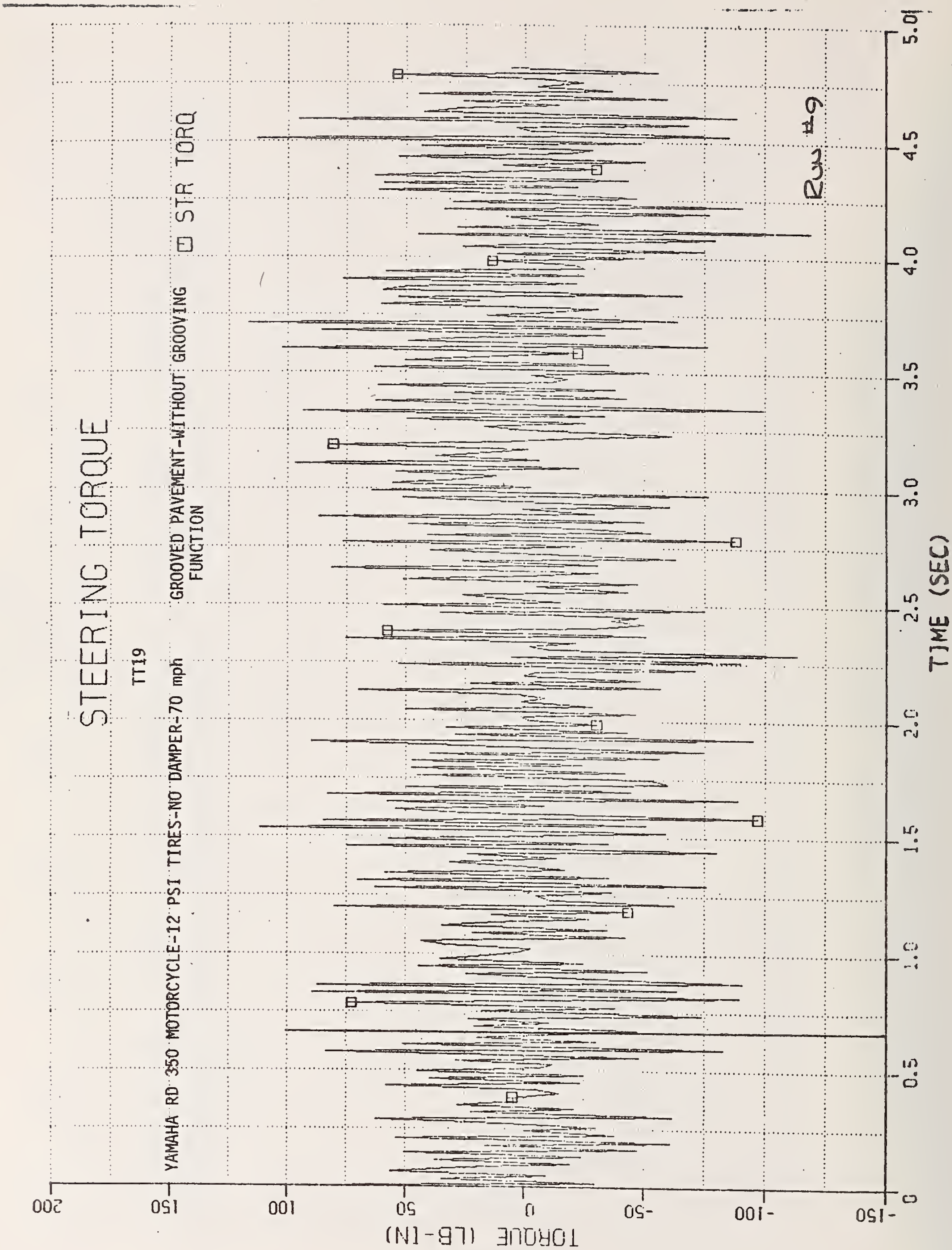
STEER, ROLL, AND YAW ANGLES
TT16
YAMAHA RD 350 MOTORCYCLE-12 PSI TIRES-WITH DAMPER-70 mph
GROOVED PAVEMENT-WITH GROOVING
FUNCTION-FILTERED DATA
□ STR(SIM)
○ STR(EXP)
△ ROLL
+ YAW
RUN #6
DEGREES
TIME (SEC)
-1
0
1
2
3
4
5
6
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

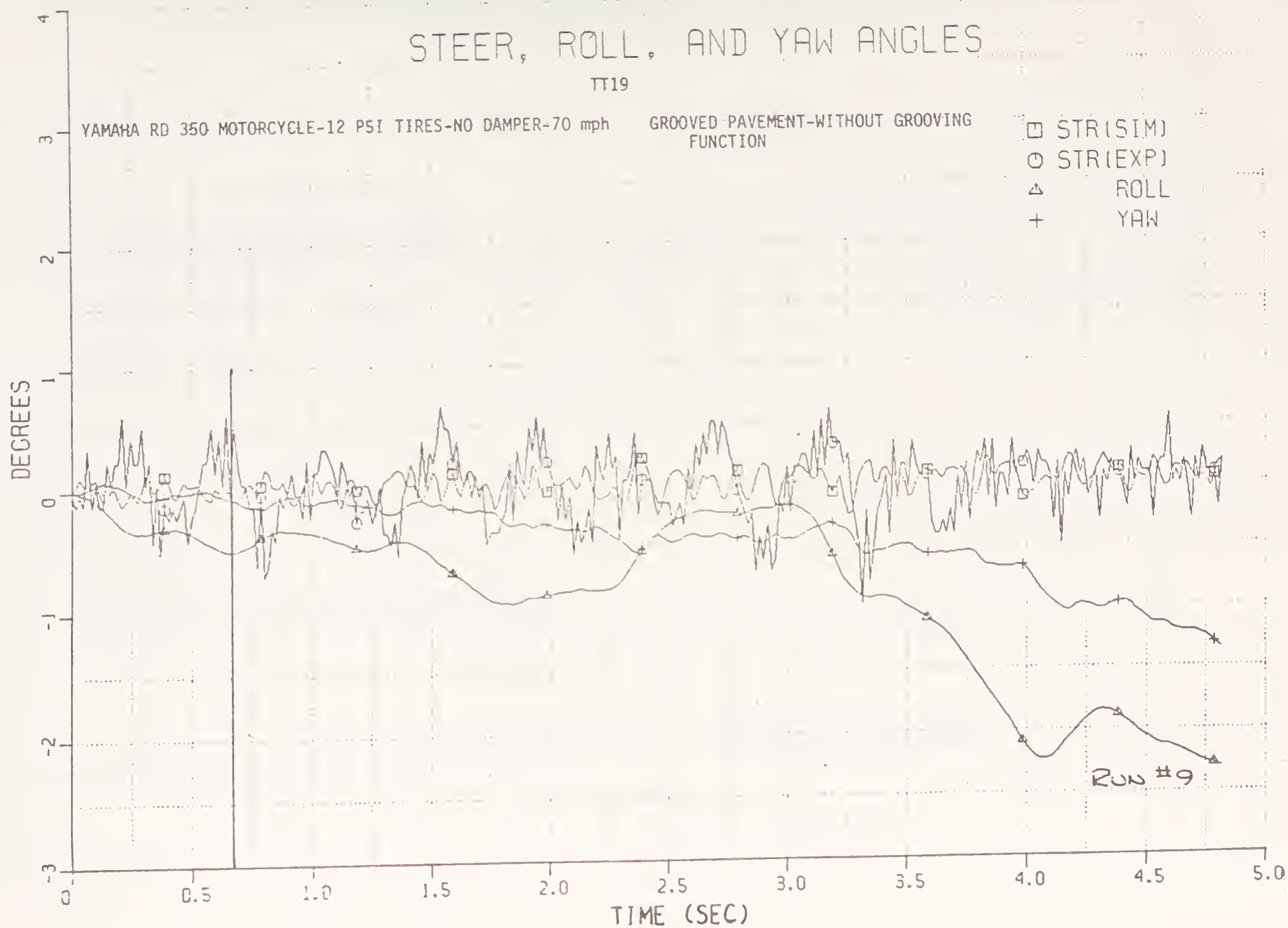

STEERING TORQUE
TT17
YAMAHA RD 350 MOTORCYCLE-12 PSI TIRES-NO DAMPER-70 mph
GROOVED PAVEMENT-WITH GROOVING
FUNCTION-FILTERED DATA
STR TORQ
RUN #7
TORQUE (LB-IN)
250
200
150
100
50
0
-50
-100
TIME (SEC)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

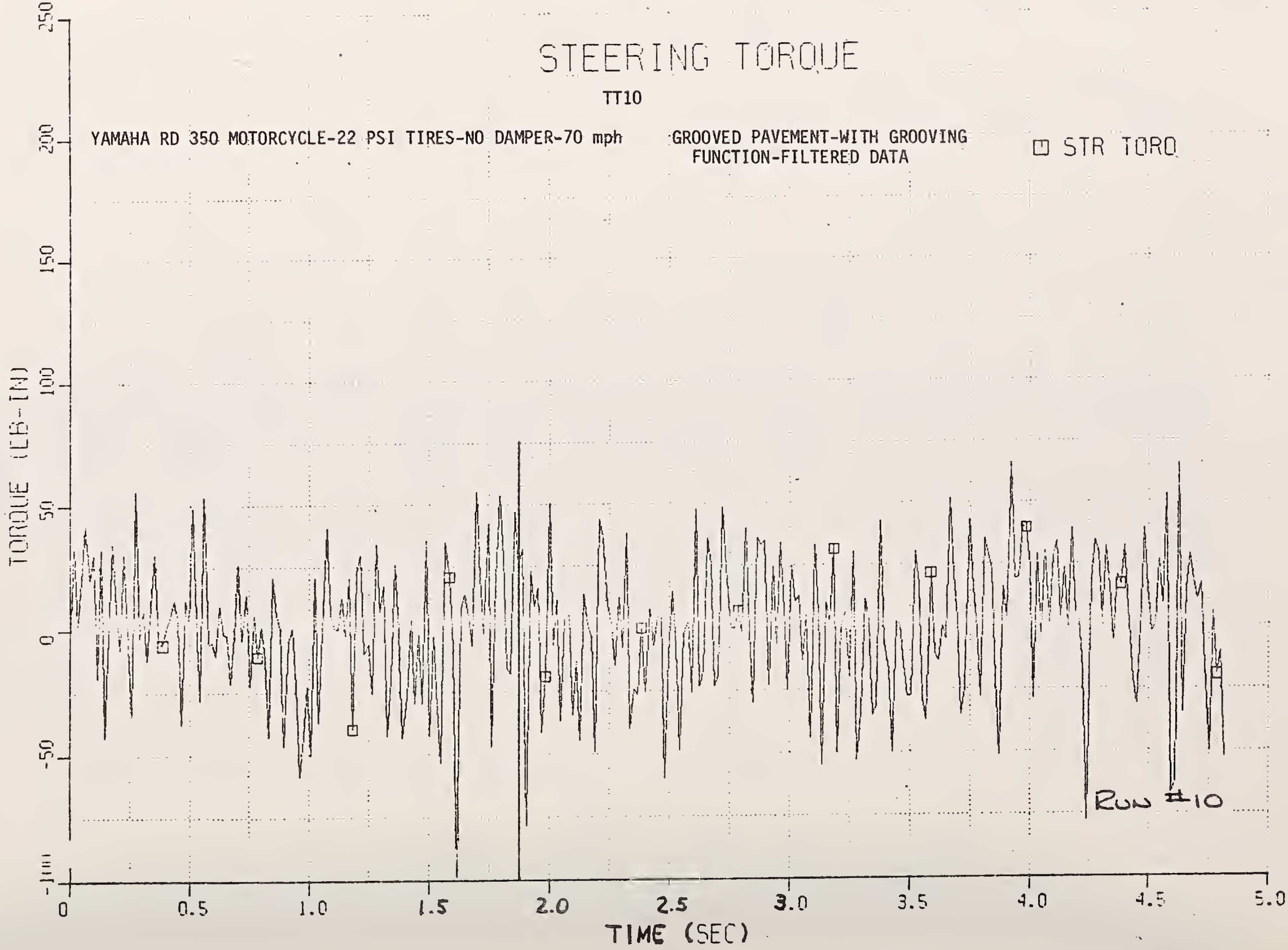

STEER, ROLL, AND YAW ANGLES
TT17
YAMAHA RD 350 MOTORCYCLE-12 PSI TIRES-NO DAMPER-70 mph
GROOVED PAVEMENT-WITH GROOVING
FUNCTION-FILTERED DATA
STR(SIM)
STR(EXP)
ROLL
YAW
DEGREES
TIME (SEC)
RUN #7

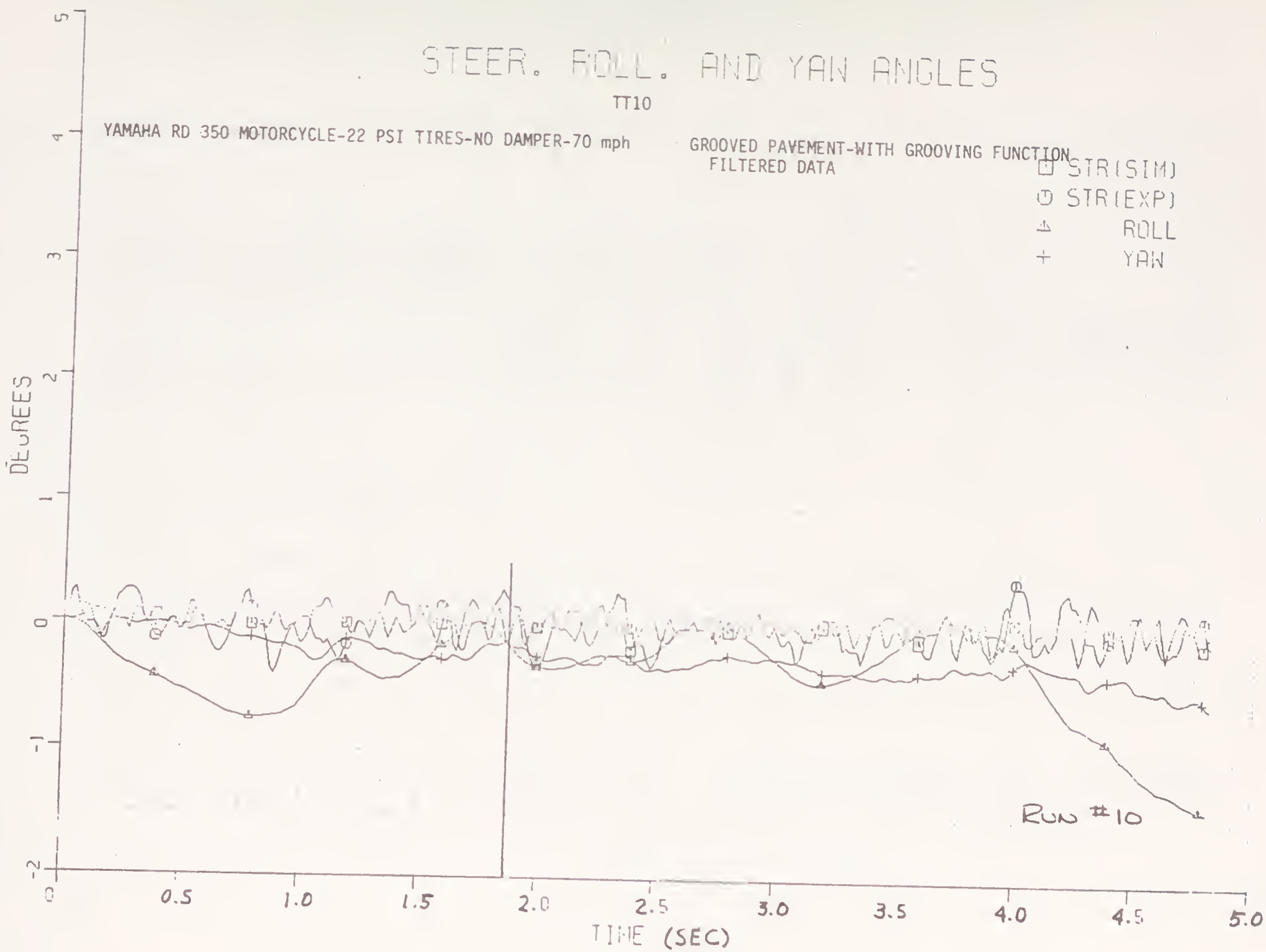

STEERING TØRQUE
TT18
YAMAHA RD 350 MOTORCYCLE-12 PSI TIRES-WITH DAMPER-70 mph
GROOVED PAVEMENT-WITHOUT GROOVING
FUNCTION-FILTERED DATA
STR TORQ
Run #8
TIME (SEC)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
TORQUE (LB-IN)
-100
-50
0
50
100
150
200
250

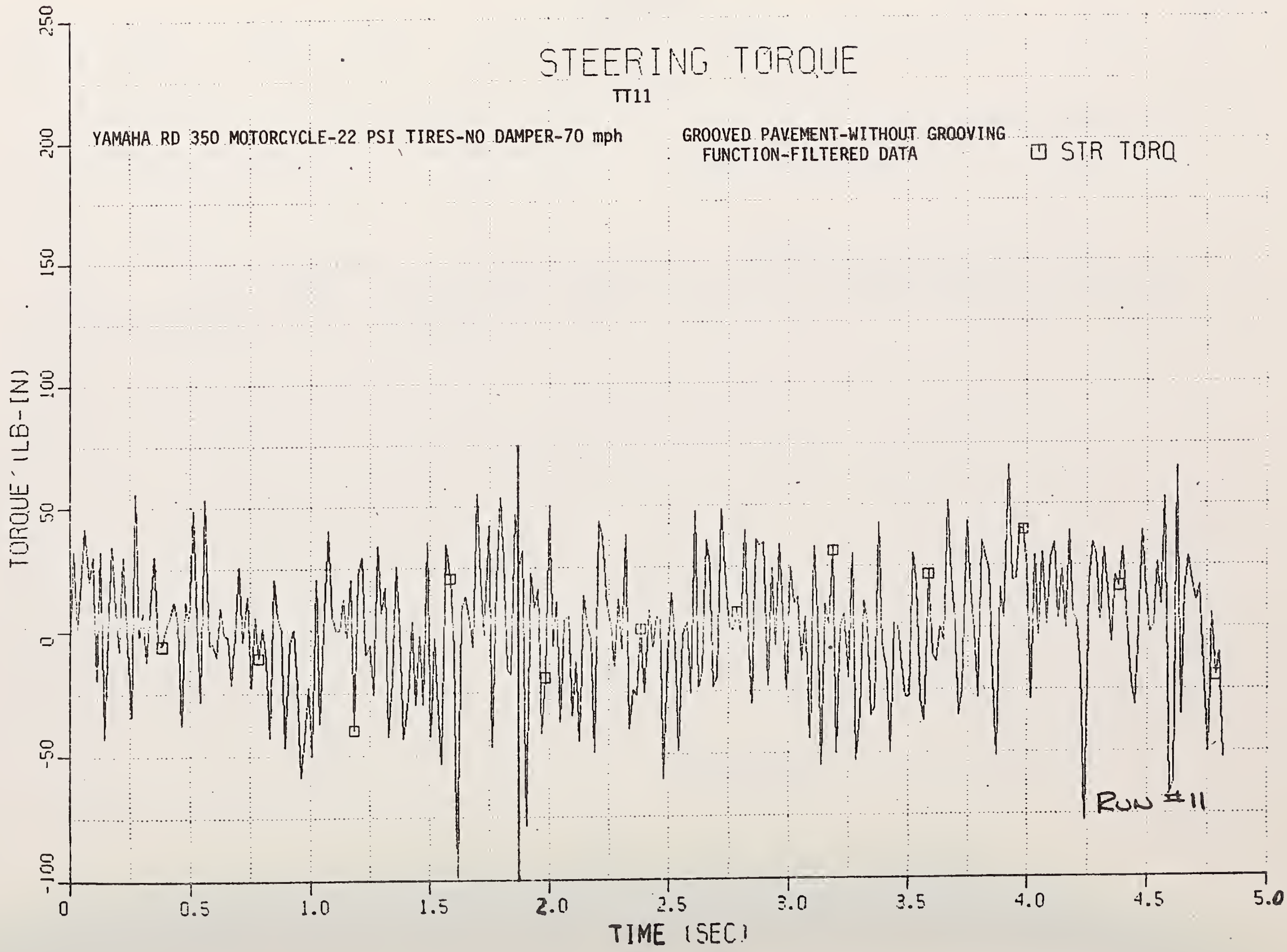

STEER, ROLL, AND YAW ANGLES
TT19
YAMAHA RD 350 MOTORCYCLE-12 PSI TIRES - WITH DAMPER-70 mph GROOVED PAVEMENT-WITHOUT GROOVING
FUNCTION-FILTERED DATA
STR(SIM)
STR(EXP)
ROLL
YAW
DEGREES
TIME (SEC)
RUN #8


STEERING TORQUE
TT19
YAMAHA RD 350 MOTORCYCLE-12 PSI TIRES-NO DAMPER-70 mph
GROOVED PAVEMENT-WITHOUT GROOVING FUNCTION
STR TORQ
Run #9
TORQUE (LB-IN)
TIME (SEC)
200
150
100
50
0
-50
-100
-150
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

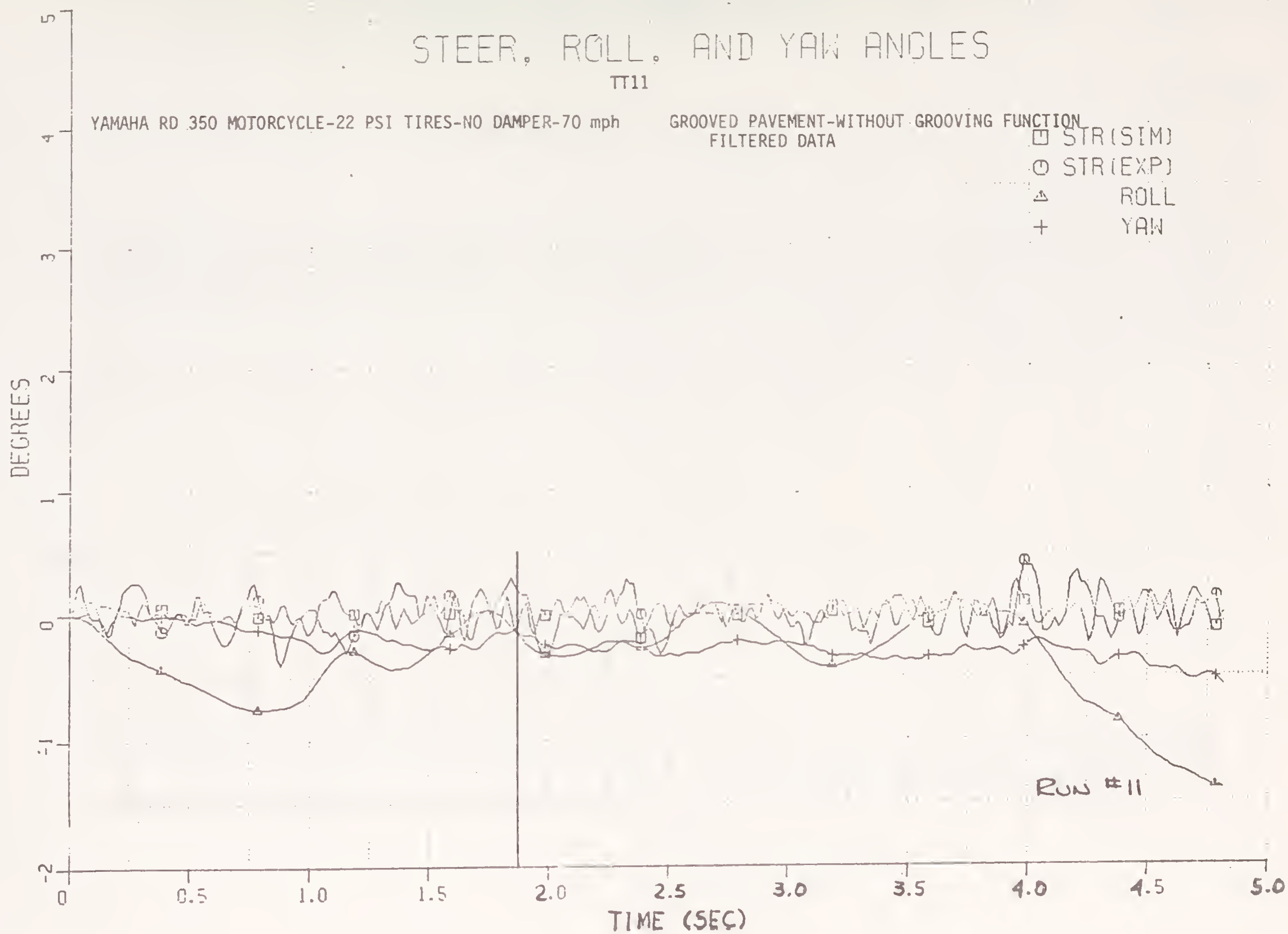

STEER, ROLL, AND YAW ANGLES
TT19
YAMAHA RD 350 MOTORCYCLE-12 PSI TIRES-NO DAMPER-70 mph
GROOVED PAVEMENT-WITHOUT GROOVING FUNCTION
STR(SIM)
STR(EXP)
ROLL
YAW
DEGREES
TIME (SEC)
RUN #9


STEERING TORQUE
TT10
YAMAHA RD 350 MOTORCYCLE-22 PSI TIRES-NO DAMPER-70 mph
GROOVED PAVEMENT-WITH GROOVING FUNCTION-FILTERED DATA
STR TORQ
TORQUE (LB-IN)
TIME (SEC)
Run #10
250
200
150
100
50
0
-50
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

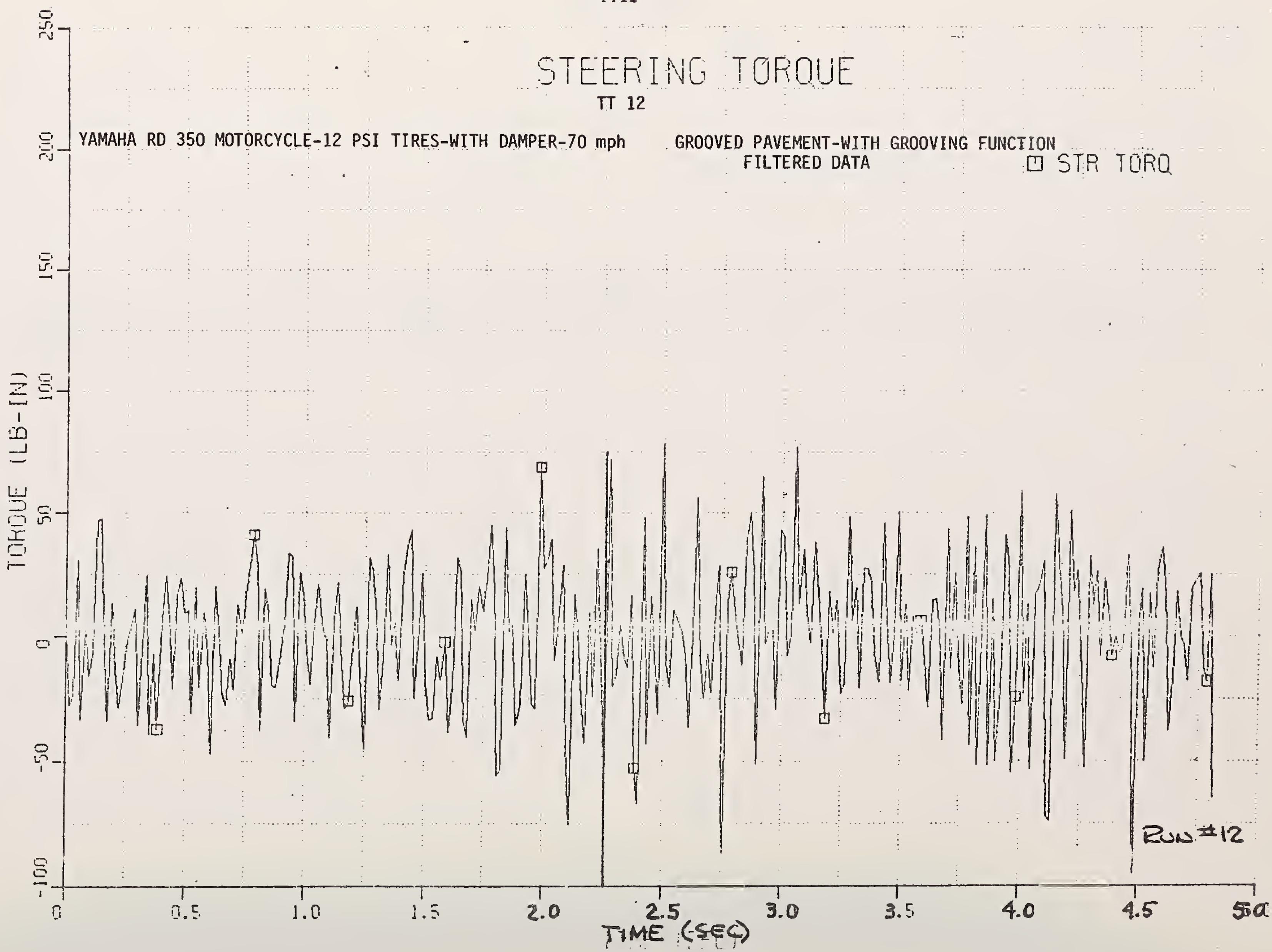

STEER. ROLL. AND YAW ANGLES
TT10
YAMAHA RD 350 MOTORCYCLE-22 PSI TIRES-NO DAMPER-70 mph
GROOVED PAVEMENT-WITH GROOVING FUNCTION
FILTERED DATA
STR(SIM)
STR(EXP)
ROLL
YAW
DEGREES
5
4
3
2
1
0
-1
-2
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
TIME (SEC)
RUN #10

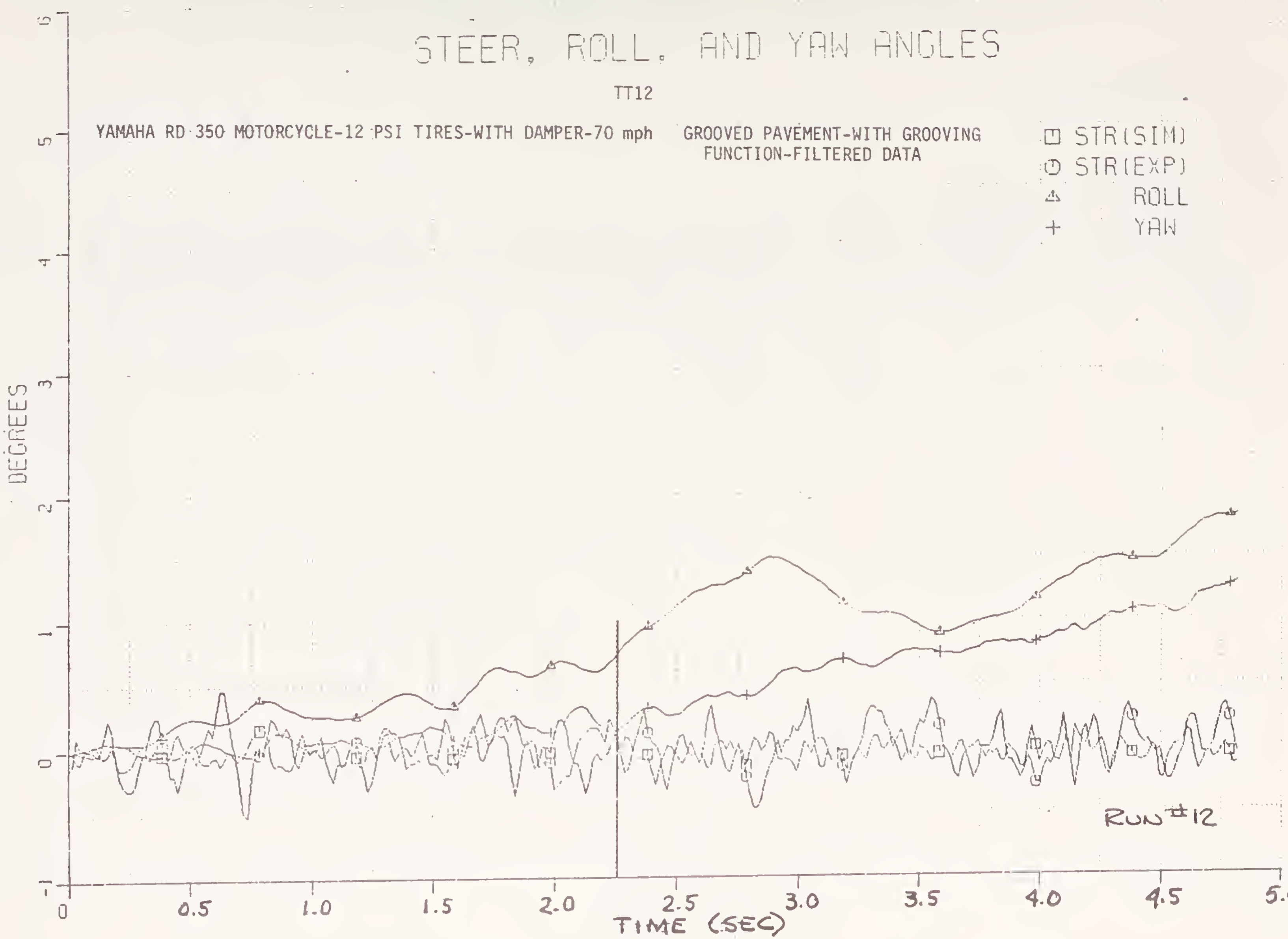


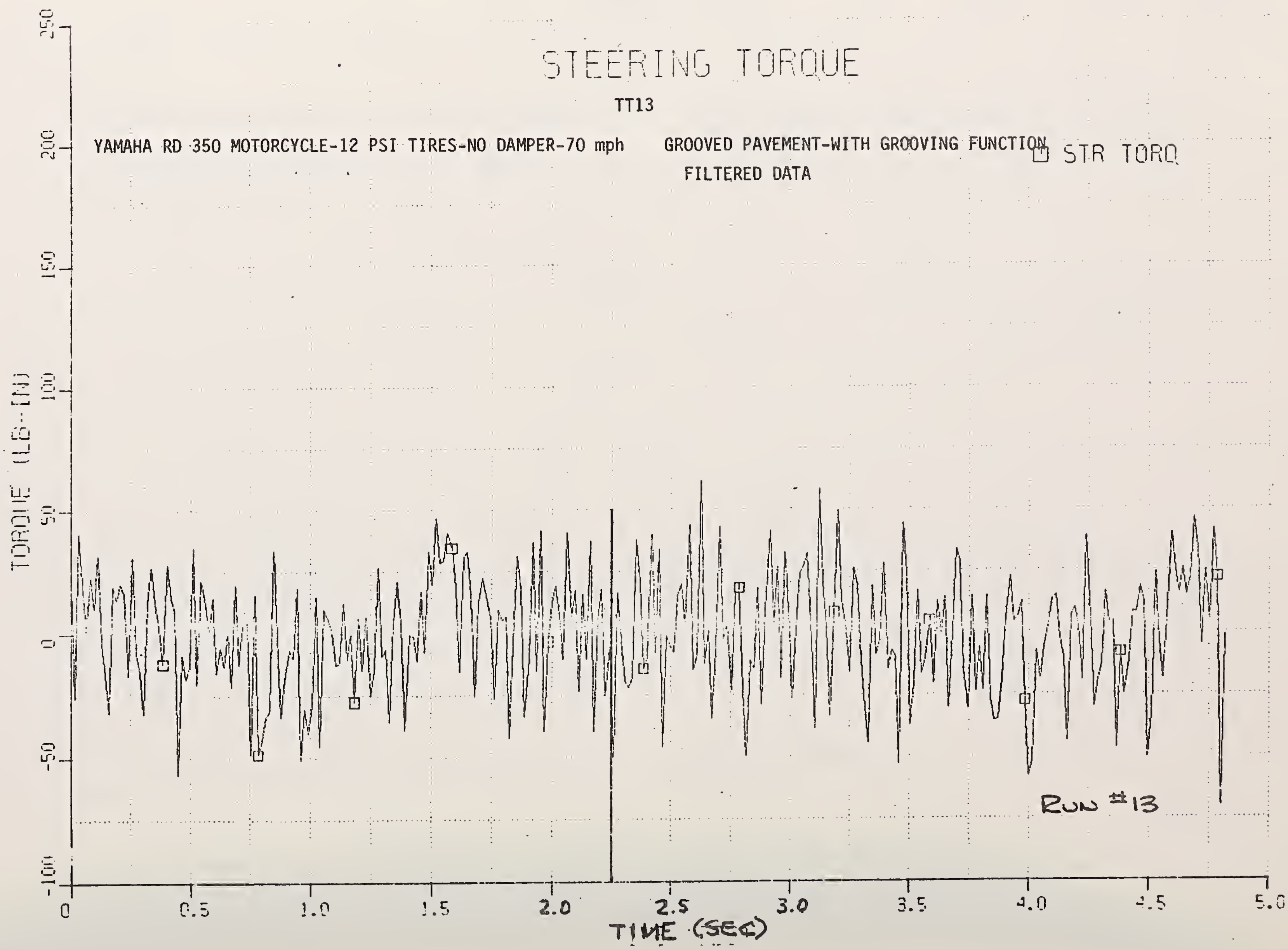
STEERING TORQUE
TT11
YAMAHA RD 350 MOTORCYCLE-22 PSI TIRES-NO DAMPER-70 mph
GROOVED PAVEMENT-WITHOUT GROOVING
FUNCTION-FILTERED DATA
STR TORQ
TORQUE (LB-IN)
250
200
150
100
50
0
-50
-100
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
TIME (SEC)
RUN #11

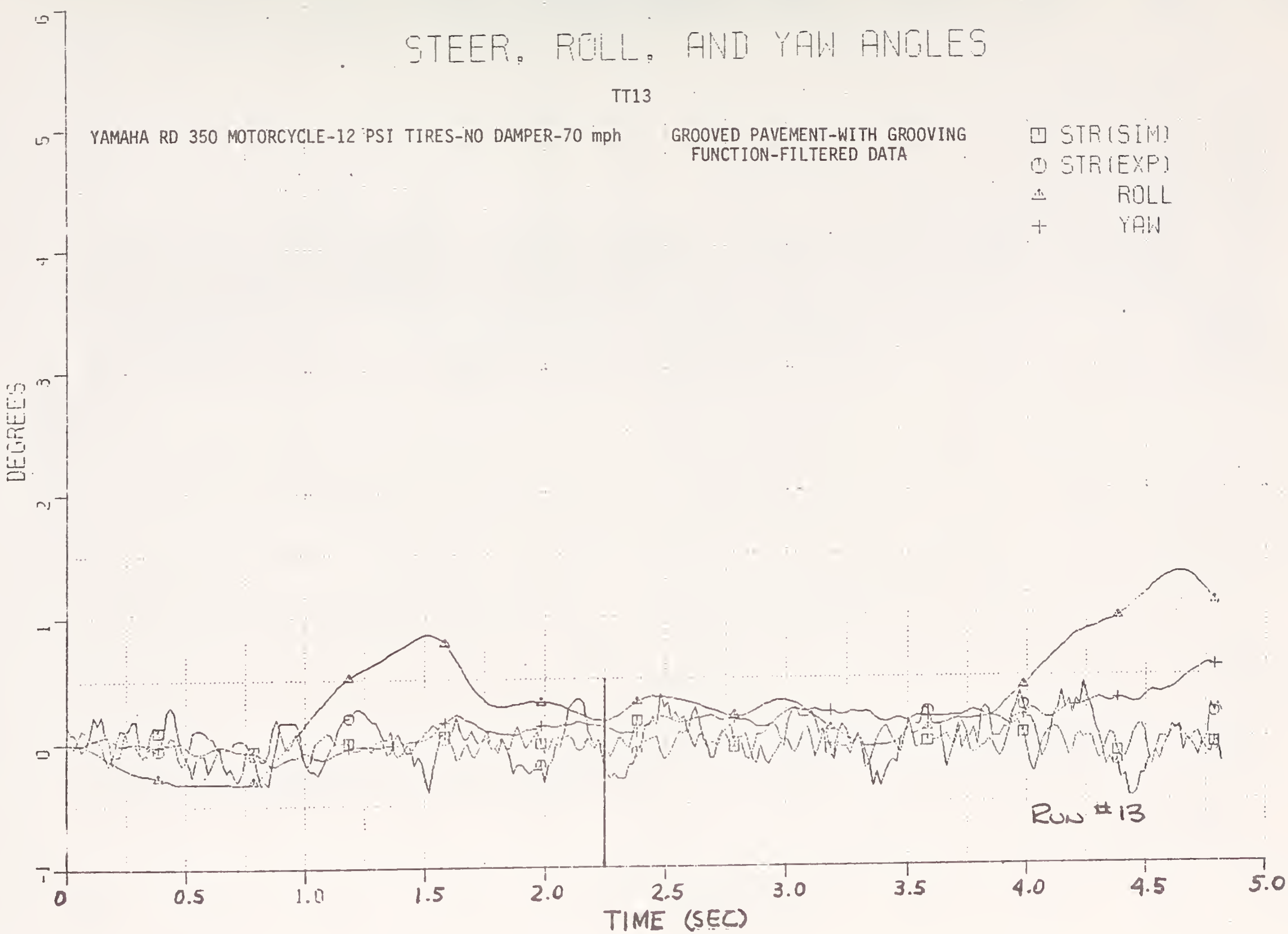

STEER, ROLL, AND YAW ANGLES
TT11
YAMAHA RD 350 MOTORCYCLE-22 PSI TIRES-NO DAMPER-70 mph
GROOVED PAVEMENT-WITHOUT GROOVING FUNCTION
FILTERED DATA
STR(SIM)
STR(EXP)
ROLL
YAW
DEGREES
5
4
3
2
1
0
-1
-2
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
TIME (SEC)
RUN #11

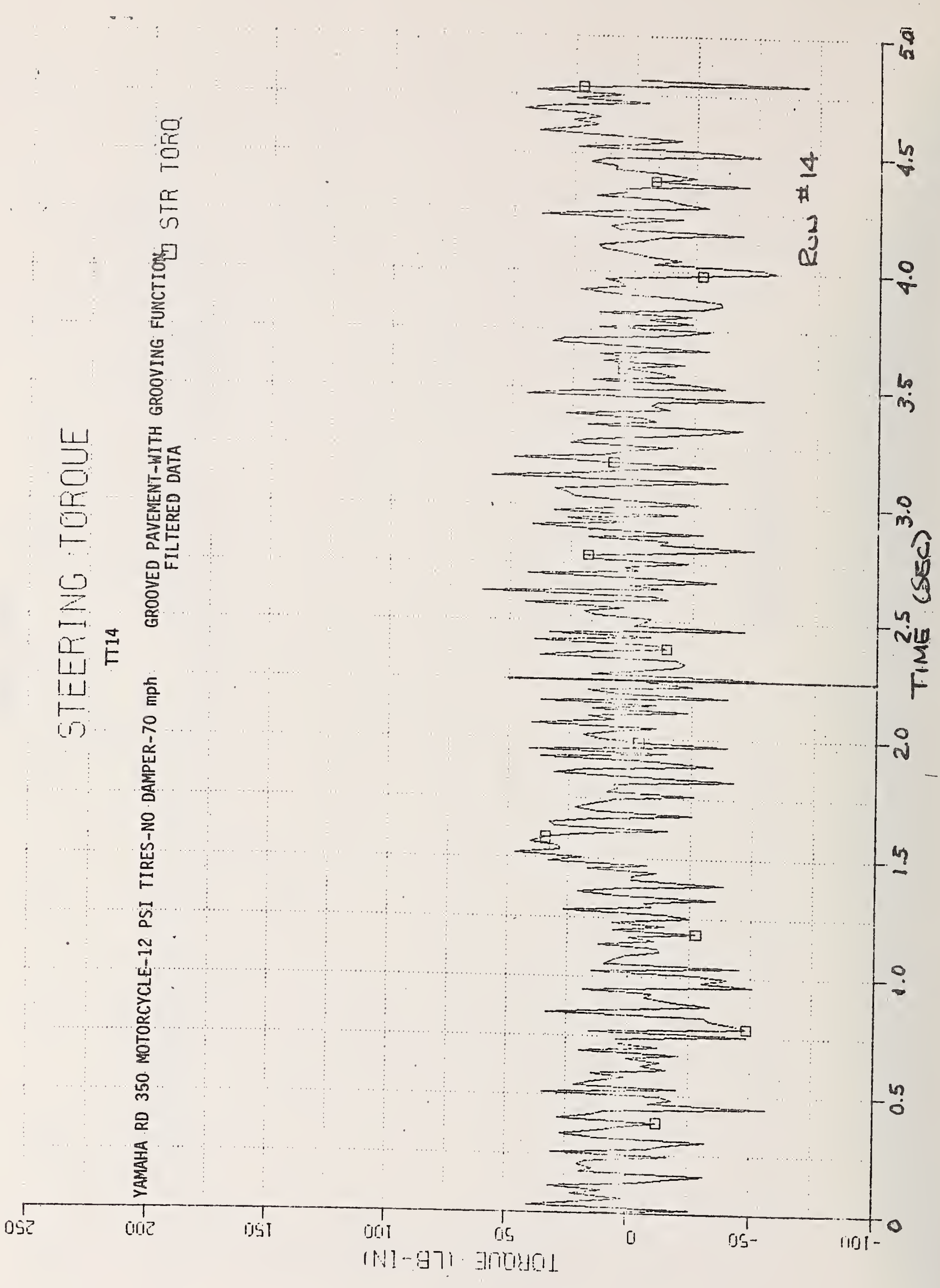
TT12

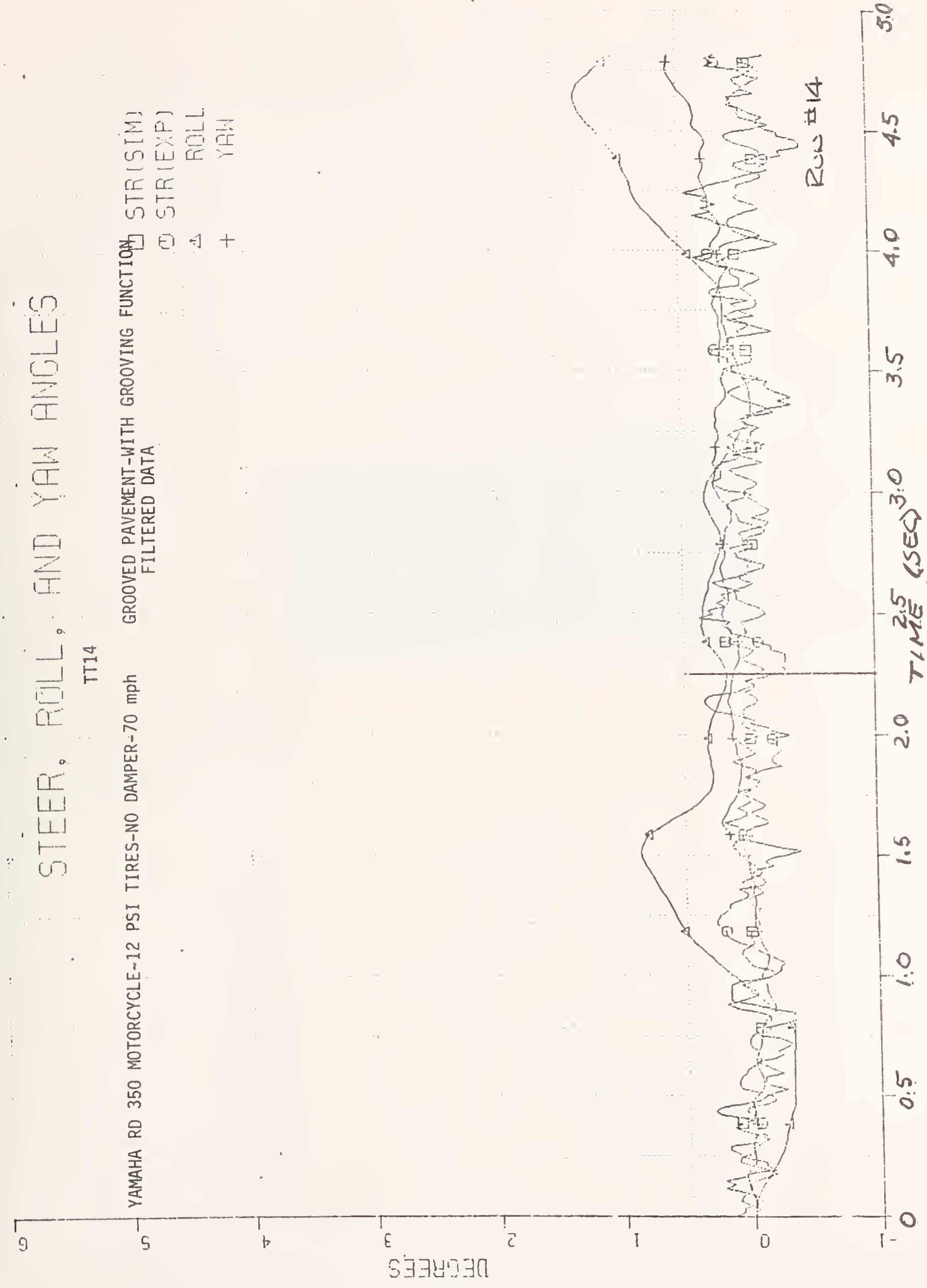

STEERING TORQUE
TT 12
YAMAHA RD 350 MOTORCYCLE-12 PSI TIRES-WITH DAMPER-70 mph
GROOVED PAVEMENT-WITH GROOVING FUNCTION
FILTERED DATA
STR TORQ
TORQUE (LB-IN)
250
200
150
100
50
0
-50
-100
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
TIME (SEC)
Run #12


STEER, ROLL, AND YAW ANGLES
TT12
YAMAHA RD 350 MOTORCYCLE-12 PSI TIRES-WITH DAMPER-70 mph
GROOVED PAVEMENT-WITH GROOVING
FUNCTION-FILTERED DATA
STR(SIM)
STR(EXP)
ROLL
YAW
DEGREES
RUN #12
TIME (SEC)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
-1
1
2
3
4
5
6


STEERING TORQUE
TT13
YAMAHA RD 350 MOTORCYCLE-12 PSI TIRES-NO DAMPER-70 mph
GROOVED PAVEMENT-WITH GROOVING FUNCTION
FILTERED DATA
STR TORQ
Run #13
TORQUE (LB-IN)
TIME (SEC)
250
200
150
100
50
0
-50
-100
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0


STEER, ROLL, AND YAW ANGLES
TT13
YAMAHA RD 350 MOTORCYCLE-12 PSI TIRES-NO DAMPER-70 mph
GROOVED PAVEMENT-WITH GROOVING
FUNCTION-FILTERED DATA
STR(SIM)
STR(EXP)
ROLL
YAW
DEGREES
-1
0
1
2
3
4
5
6
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
TIME (SEC)
Run #13


STEERING TORQUE
TT14
YAMAHA RD 350 MOTORCYCLE-12 PSI TIRES-NO DAMPER-70 mph
GROOVED PAVEMENT-WITH GROOVING FUNCTION
FILTERED DATA
STR TORQ
RUN #14
TIME (SEC)
TORQUE (LB-IN)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
-100
-50
0
50
100
150
200
250


STEER, ROLL, AND YAW ANGLES
TT14
YAMAHA RD 350 MOTORCYCLE-12 PSI TIRES-NO DAMPER-70 mph
GROOVED PAVEMENT-WITH GROOVING FUNCTION
FILTERED DATA
□ STR(SIM)
⊙ STR(EXP)
△ ROLL
+ YAW
RUN #14
DEGREES
6
5
4
3
2
1
0
-1
TIME (SEC)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

FHWA
R&D