technical paper

SECOND INTERNATIONAL CONGRESS ON AUTOMOTIVE SAFETY

Theme

Motorcycle and Recreational Vehicle Safety

Paper No. 73020

SIMULATION STUDY OF MOTORCYCLE STABILITY AT HIGH SPEED

R. Douglas Roland
Calspan Corporation

July 16–18, 1973

Hotel St. Francis
San Francisco, California, USA

ABSTRACT

A comprehensive digital computer simulation of a two-wheel vehicle and rider has been developed and is being used to study motorcycle stability and handling. The simulation is based on a nonlinear mathematical model with eight degrees of freedom, including steer and rider lean. Tire side force and aligning torque as nonlinear functions of slip angle, camber angle and vertical load, aerodynamic drag, pitching moment and steering torque, steering damping, and gyroscopic effects of the engine and wheels are modeled as well as fork rake angle, steering trail, and the basic physical characteristics of the motorcycle frame, steering assembly, and rider. These parameters are input data to the computer simulation which produces output in the form of time histories of the motion variables of the vehicle. The two-wheel vehicle simulation has been validated by comparison with experimental tests using an instrumented vehicle.

A combined analytical and experimental research program has been conducted as a coordinated effort by Calspan Corporation and the Harley-Davidson Motor Company, Inc. to study the weave instability phenomenon which can occur in motorcycles at high speed. "Speedman's wobble", as it has been called, is characterized by coupled steer-roll-yaw motions of the vehicle and has long been recognized by theoretical dynamicists. The influence of several motorcycle characteristics on weave instability have been evaluated in the context of total system performance by simulating the disturbance-response behavior at high speed.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SIMULATION STUDY OF MOTORCYCLE STABILITY AT HIGH SPEED

1. INTRODUCTION

The potential for high speed instability in two-wheel vehicles has long been recognized by theoretical dynamicists. This phenomenon is manifested as a coupled roll-yaw-steer motion of the vehicle at high speed (generally above legal highway limits). It is characterized by near-zero damping of the oscillations at frequencies in the neighborhood of 2 to 3 Hz., depending on the specific vehicle configuration. This condition, called "speedman's wobble" by Pearsall (1922) and defined as the "weave" mode of oscillation by Sharp (1971), has been treated in a number of studies, but no clear and complete understanding of it has resulted.

Published works on the single track vehicle date back to the turn of the century. Unfortunately many of these mathematical treatments neglected the effects of gyroscopic moments, tire mechanics, and high speed operation. Dohring (1956), for example, discussed the steering wobble of high speed motorcycles but neglected the interaction between the front fork assembly and the rear frame and greatly oversimplified the tire mechanics, and Collins (1963) performed a mathematical analysis of the effects of motorcycle parameters on stability but also neglected important tire effects.

Singh's analysis (1964) was the most comprehensive at that time. This work involved the computation of stability coefficients using a digital computer to solve the linearized equations of motion of the motorcycle. Although tire mechanics were analyzed, automobile tire data were used for lack of actual motorcycle tire data. The effects of numerous motorcycle parameter variations were studied using nondimensionalized parameters and stability coefficients; however, the study was not directly related to the effects of design changes on high speed stability.

The discussion which follows refers to three primary modes of motorcycle motion as defined by Sharp in his treatment of motorcycle stability characteristics:

(1) the nonoscillatory "capsize mode,"
(2) the oscillatory "weave mode" characterized by oscillations ranging in frequency from about 0.2 to 3.4 Hz., depending on motorcycle speed, and
(3) the oscillatory "wobble mode" characterized by steering oscillations at higher steering frequencies ranging from 4 to 10 Hz., depending almost entirely on motorcycle configuration and independent of speed.

Sharp determined the natural frequencies and damping coefficients of these modes for several design configurations using a comprehensive linearized mathematical model of the motorcycle.

Recently, Weir (1972) studied the closed-loop rider-vehicle system using a linear four-degree-of-freedom vehicle model. Several rider control feedback loops were studied and the most significant loop closures were identified. The effect of motorcycle design on rider-vehicle system performance was investigated using a representative rider model. Weir concluded that the primary rider control task is the stabilization of the nonoscillatory capsize mode and that the high frequency weave and wobble modes are largely unaffected by rider control although, if lightly damped, they can be excited by rider control actions.

About three years ago, Rice and Roland undertook a brief study of bicycle stability and control. One of the principal results of this work was the development of a mathematical model of the two-wheel vehicle. For the last two years, Roland has been engaged in a general program of research on bicycle dynamics aimed at the development and validation of a comprehensive digital computer simulation of a bicycle and rider based on the previous mathematical model. The basic equations of motion of the mathematical model are generally valid for all single-track two wheel vehicles. Furthermore, the computer simulation program was written in a generalized format which allowed easy modification and extension for studying a wide range of two-wheel vehicles. Thus, the program provided an ideal basis for the development of a computer simulation of motorcycle dynamics.

The subject of this paper is the application of this two-wheel vehicle simulation to the study of the weave mode of oscillation of the motorcycle at high speed. The primary objective was to determine what changes could be made in the design of a specific motorcycle to prevent high speed weave instability. The use of simulation avoids the difficulties encountered in maintaining strict control of the many interacting variables affecting experimental results under actual operating conditions. Simulation of the weaving motion of a motorcycle resulting from a rider-induced disturbance input is ideally suited to this type of study since individual vehicle design parameters can be easily changed and the resultant effects on motorcycle motions directly observed.

2. TWO-WHEEL VEHICLE SIMULATION

The vehicle-rider model* on which the simulation is based 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

*The analysis is described in "An Evaluation of the Performance and Handling Qualities of Bicycles," by R.S. Rice and R.D. Roland, Calspan Report No. VJ-2888-K for the National Commission on Product Safety, 1970.

Figure 1). The basic physical parameters of the vehicle which are included in the mathematical analysis are shown in Figure 2, 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 following factors are included in the analysis:

(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 considered.

(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) The rider is assumed to be rigidly attached to the rear frame (the rider lean degree of freedom was effectively locked-out).

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

(6) External torques acting about the steer axis include the moments due to the lateral and vertical tire forces, tire aligning torque, and a couple due to the aerodynamic drag force on the windshield. The gyroscopic moments of the wheels and engine are included.

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

(8) 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

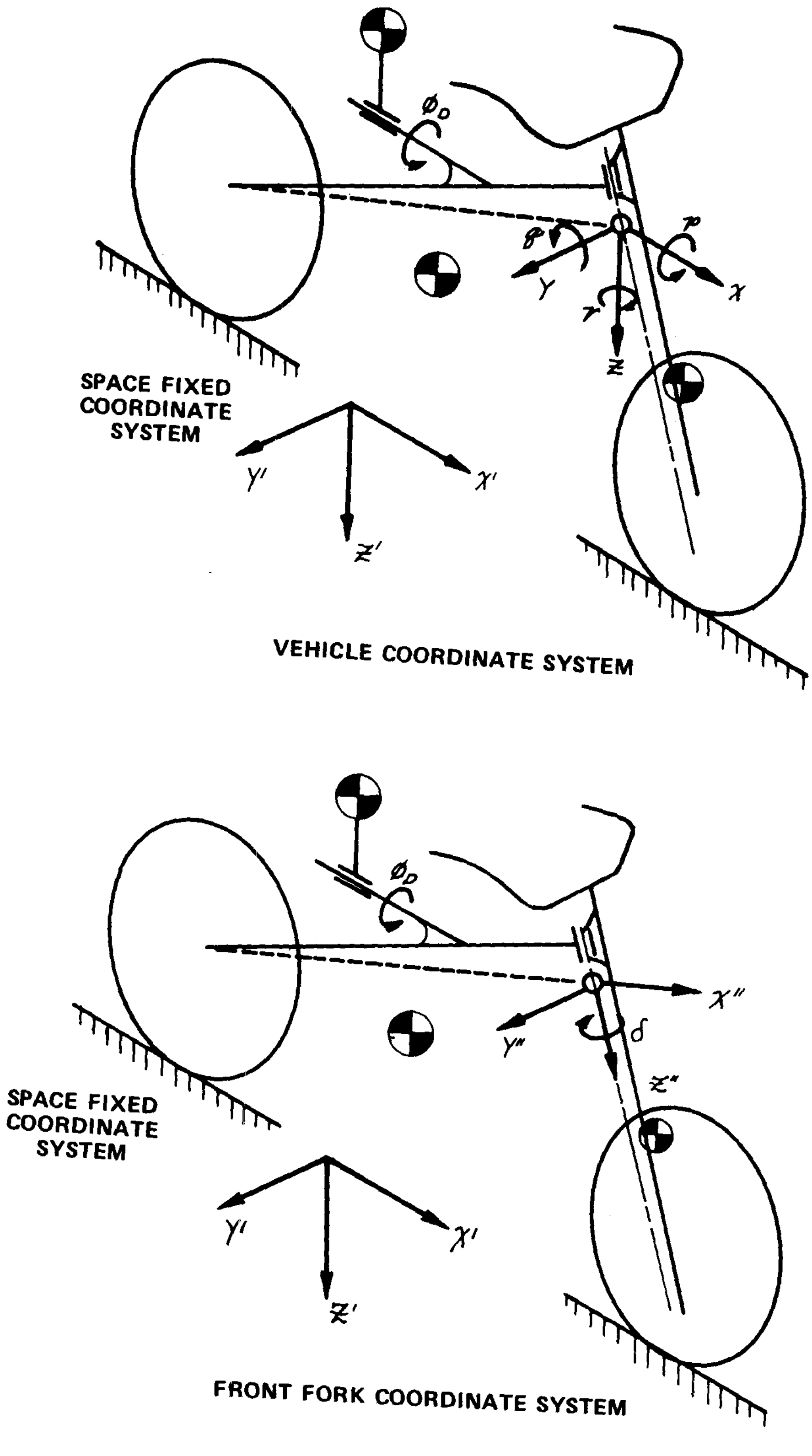

Figure 1. Two-Wheel Vehicle Model

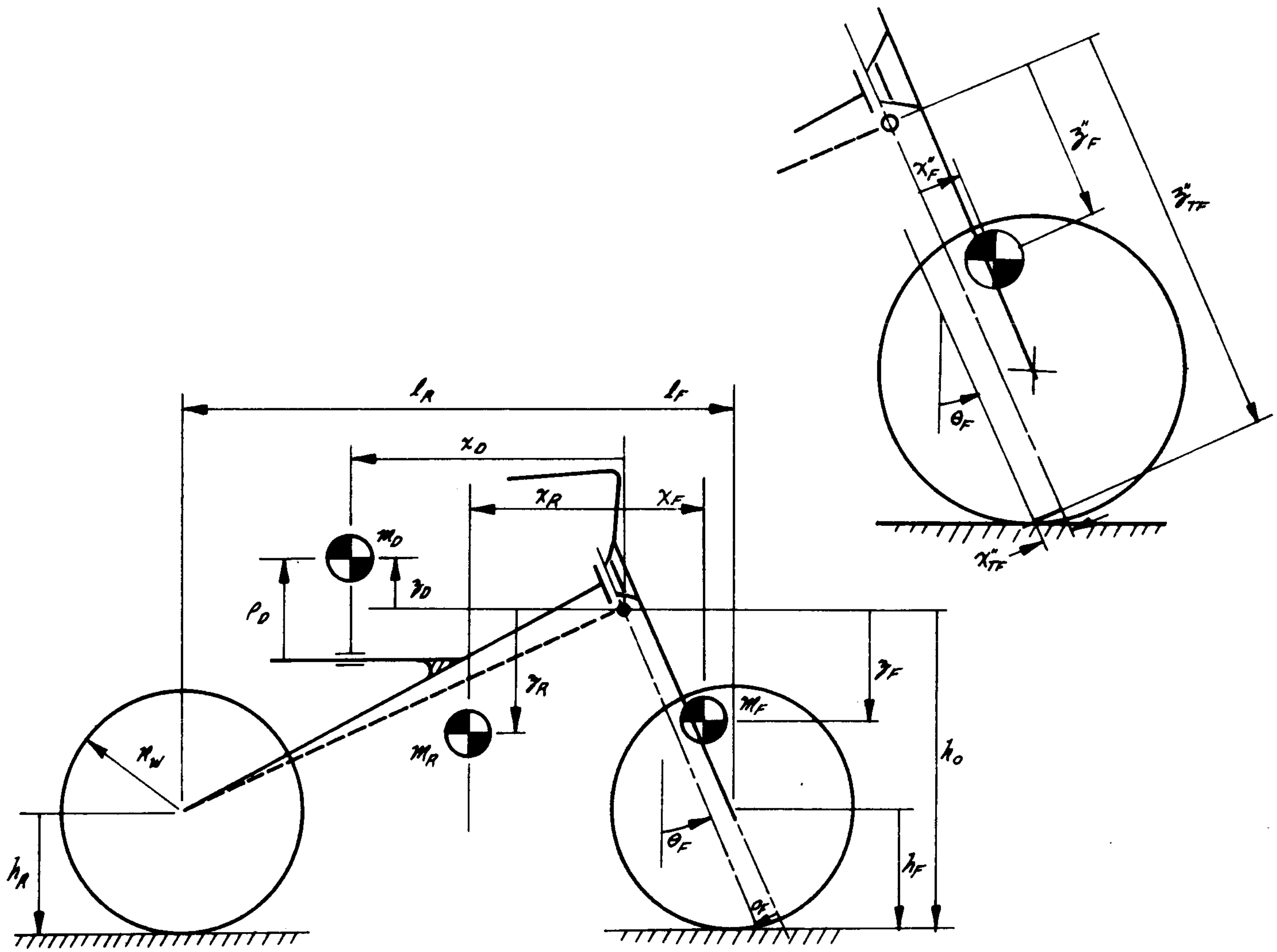

Figure 2. Characteristic Dimensions of Motorcycle Model

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.

Although the two-wheel vehicle simulation includes a rider control model capable of stabilizing and guiding the vehicle by sensing position and motion variables and generating steer and lean control torques, the simulated disturbance response tests were performed with a rigid rider and "hands off" steering. The high speed weave phenomenon can be studied independently of rider control since the frequency of the oscillation is high (relative to rider response) and only small motions occur about the upright position. This procedure is consistent with the full scale experimental test methods.

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. The total cost of both the simulation and output processor programs is approximately ten dollars per problem.

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. Typical input data are listed in Figure 3.

The digital computer simulation program consists basically of the application of a modified Runge-Kutta step-by-step procedure to integrate 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.

3. MEASURED PHYSICAL CHARACTERISTICS OF THE MOTORCYCLE

Required input data to the computer simulation includes a detailed list of the physical characteristics of the motorcycle. These data were measured for the actual test motorcycle in an effort to achieve the closest possible correspondence between simulation and experimental validation results and to provide maximum accuracy in predicting the effects of design changes. The Harley-Davidson Electra-Glide motorcycle was used as the base configuration for the design parameter studies performed with the simulation. The specific physical characteristics and their measured values are shown in Figure 3. All motorcycle characteristics except those of the tires were measured by the Harley-Davidson Motor Company.

The moments of inertia were determined using the torsional pendulum method. The steering damping was determined by calculating the logarithmic decrement of the oscillatory steering motion with the front

HIGH SPEED MOTORCYCLE STABILITY STUDY (80 MPH) 22MAY'73
(1) STANDARD CONFIGURATION

WHEELBASE (IN)	61.50
TOTAL WEIGHT OF MOTORCYCLE (LB)	790.00
PORTION OF TOTAL MOTORCYCLE WEIGHT ON FRONT WHEEL (PERCENT)	37.90
LOCATION OF TOTAL MOTORCYCLE C.G. ABOVE GROUND (IN)	17.90
ROLL MOMENT OF INERTIA OF THE TOTAL MOTORCYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	226.00
PITCH MOMENT OF INERTIA OF THE TOTAL MOTORCYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	1115.00
YAW MOMENT OF INERTIA OF THE TOTAL MOTORCYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	1000.00
ROLL-YAW PRODUCT OF INERTIA OF TOTAL MOTORCYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	-7.30

WEIGHT OF RIDER (LB)	220.00
PORTION OF RIDER WEIGHT ON FRONT WHEEL (PERCENT)	26.00
HEIGHT OF RIDER C.G. ABOVE GROUND (IN)	40.00
HEIGHT OF SADDLE ABOVE GROUND (IN)	40.10
ROLL MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	90.00
PITCH MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	40.00
YAW MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	30.00
ROLL-YAW PRODUCT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	0.0

WEIGHT OF FRONT FORK ASSEMBLY (FORK,WHEEL,AND HANDLE BARS),(LB)	128.00
PERPENDICULAR DISTANCE FROM C.G. OF FRONT FORK ASSEMBLY TO STEER AXIS (IN)	1.90
DISTANCE PARALLEL TO STEER AXIS FROM C.G. OF FRONT FORK ASSEMBLY TO FRONT WHEEL CENTER (IN)	12.80
ROLL MOMENT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT AN AXIS PERPENDICULAR TO THE STEER AXIS THROUGH C.G. OF ASSEMBLY (LB-IN-SEC SQ)	69.00
PITCH MOMENT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT AN AXIS THROUGH THE C.G. OF THE ASSEMBLY (LB-IN-SEC SQ)	67.80
YAW MOMENT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT THE STEER AXIS (LB-IN-SEC SQ)	16.40
ROLL-YAW PRODUCT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT AN AXIS THROUGH THE C.G. OF THE ASSEMBLY (LB-IN-SEC SQ)	3.82

CASTER ANGLE OF THE STEER AXIS (DEG)	30.70
NOMINAL STEERING TRAIL (IN)	5.36
FRONT TIRE PNEUMATIC TRAIL (IN)	0.50
STEERING VISCOUS DAMPING COEFFICIENT (IN-LB/DEG/SEC)	0.59
STEERING HYDRAULIC DAMPING COEFFICIENT (IN-LB/(DEG/SEC)SQ)	0.0
SPIN MOMENT OF INERTIA OF THE FRONT WHEEL (LB-IN-SEC SQ)	7.20
SPIN MOMENT OF INERTIA OF THE REAR WHEEL (LB-IN-SEC SQ)	11.60

UNDEFLECTED FRONT WHEEL ROLLING RADIUS (IN)	13.20
FRONT TIRE SECTION WIDTH (IN)	5.10
RADIAL STIFFNESS OF FRONT TIRE (LB/IN)	500.00
ROLLING RESISTANCE COEF. OF FRONT TIRE (LB/LB)	0.0
VERTICAL LOAD-SIDE FORCE COEFFICIENT OF FRONT TIRE (LB/LB/LB)	0.0
SLIP ANGLE-SIDE FORCE COEFFICIENT OF FRONT TIRE (LB/LB/DEG)	0.101
SLIP ANGLE CUBED-SIDE FORCE COEFFICIENT OF FRONT TIRE (LB/LB/DEG CU)	-0.00041
INCLINATION ANGLE-SIDE FORCE COEFFICIENT OF FRONT TIRE (LB/LB/DEG)	0.01150
AERODYNAMIC DRAG COEFFICIENT (DIMENSIONLESS)	1.20
AERODYNAMIC LIFT COEFFICIENT (DIMENSIONLESS)	0.0
TOTAL FRONTAL AREA (IN SQ)	1193.00
LATERAL OFFSET OF CENTER OF PRESSURE FROM MOTORCYCLE CENTER LINE (IN)	0.0
HEIGHT OF CENTER OF PRESSURE ABOVE GROUND (IN)	24.00
AERODYNAMIC DRAG COEFFICIENT OF WINDSHIELD (DIMENSIONLESS)	1.00
WINDSHIELD FRONTAL AREA (IN SQ)	500.00
LOCATION OF WINDSHIELD CENTER OF PRESSURE FORWARD OF THE STEER AXIS (IN)	12.00

UNDEFLECTED REAR WHEEL ROLLING RADIUS (IN)	13.20
REAR TIRE SECTION WIDTH (IN)	5.10
RADIAL STIFFNESS OF REAR TIRE (LB/IN)	500.00
ROLLING RESISTANCE COEF. OF REAR TIRE (LB/LB)	0.0
VERTICAL LOAD-SIDE FORCE COEFFICIENT OF REAR TIRE (LB/LB/LB)	0.0
SLIP ANGLE-SIDE FORCE COEFFICIENT OF REAR TIRE (LB/LB/DEG)	0.101
SLIP ANGLE CUBED-SIDE FORCE COEFFICENT OF REAR TIRE (LB/LB/DEG CU)	-0.00041
INCLINATION ANGLE-SIDE FORCE COEFFICIENT OF REAR TIRE (LB/LB/DEG)	0.01150

Figure 3. Simulation Input Data for the Standard Electra Glide Motorcycle Configuration

assembly restrained by a torsion rod. Frontal areas were determined from planimeter measurements of photographs of the various configurations. Drag coefficients were computed from maximum vehicle speed and engine torque-speed data. Center of pressure heights were based on data relating wheel loadings and speed.

Because of the small amplitude of steer and roll motions which occur in the weave oscillation, the tires are operating well within their linear performance range. Thus, the important tire characteristics are the cornering coefficient and the camber coefficient. These are the normalized lateral force per degree of tire slip angle and the normalized lateral force per degree of tire inclination angle, respectively. The normalized lateral force is the actual lateral force divided by the vertical load on the tire.

Data were obtained from the Dunlop Tire and Rubber Corporation on several motorcycle tires in the size range of 3.25 x 18 to 4.10 x 18. These data included lateral force as a function of slip angle and inclination angle for several loadings and inflation pressures. From these data, typical tire characteristics were computed for the appropriate size, loading, and pressure of the tires used on the test motorcycle.

4. SIMULATED DESIGN PARAMETER STUDY

The primary objective of the program was the quantitative determination of the effects of all significant motorcycle design parameters on the high speed weave oscillation. This was achieved by using the two-wheel vehicle simulation in a study which included variations of seventeen different motorcycle parameters. Simulation runs of 5 seconds duration (simulated real time) were made of motorcycle response after a lateral force disturbance. Quantitative evaluations of the effect of each parameter change were computed from resultant weave motions.

In the development of the simulated disturbance response test, several conditions were imposed. The simulated motorcycle was initially traveling at steady speed in a straight path. A "hands off" steering condition was assumed throughout the run. The disturbance input used to excite the simulated weave oscillation was modeled after the method actually used by the rider in the experimental tests. By quickly pivoting at the hips, the rider created a lateral force on the motorcycle frame at the seat. This lateral force pulse caused a small frame roll angle which excited the motorcycle into weave motion. The simulated disturbance input was also a lateral force applied at the approximate location of the saddle. This disturbance was one cycle of a 2 Hz. sinusoidal force with an amplitude of 100 pounds (Figure 4). The amplitude of the sinusoidal force was selected to provide an initial roll angle oscillation amplitude nearly equal to that measured in the experimental tests with the standard Electra-Glide motorcycle configuration at 80 mph.

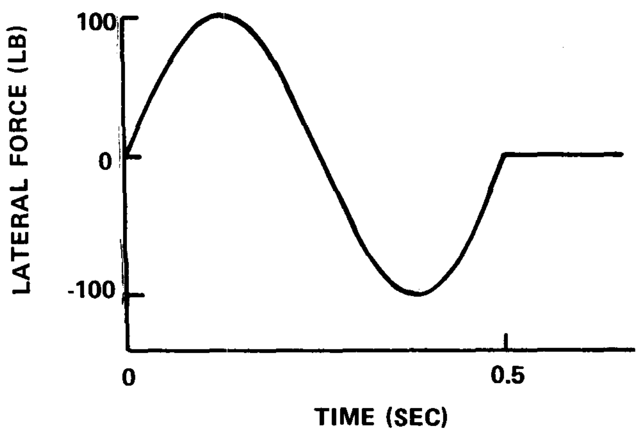

Figure 4. Simulated Distrubance Input

In order to establish the validity of the simulation, experimental tests were performed and the results were compared with simulated disturbance response data. The test motorcycle was a standard Electra-Glide equipped with saddle bags and a tour pack which were intentionally overloaded to amplify the weave motion. This was the "standard" configuration from which the physical characteristics were measured. The motorcycle was instrumented to record time histories of steer angle, roll angle, lateral acceleration and speed. Experimental test runs were performed at 70, 80, and 87 mph with the standard configuration, as well as other configurations with variations in the rear frame, front assembly, and wheel moments of inertia.

Figure 5 shows a comparison of the experimental and simulated responses for the standard configuration at 80 mph. In frequency (2.0 Hz.), phase angle (steer leads roll by a phase angle of about 110 degrees), and the ratio of steer amplitude to roll amplitude, the simulation results agree very closely with experimental data.

An initial simulation study was performed to determine the effects of seventeen motorcycle design and operational parameters on the amplitude and damping of the weave oscillation. Each of these parameters was independently varied (arbitrarily ±20% from the standard configuration) while attempting to maintain constant values for all others. This first series of runs identified several parameter changes which tended toward improved behavior.

Table 1 shows the results of these parameter variation runs as well as those of the standard configuration at 70, 80 and 87 mph. All runs,

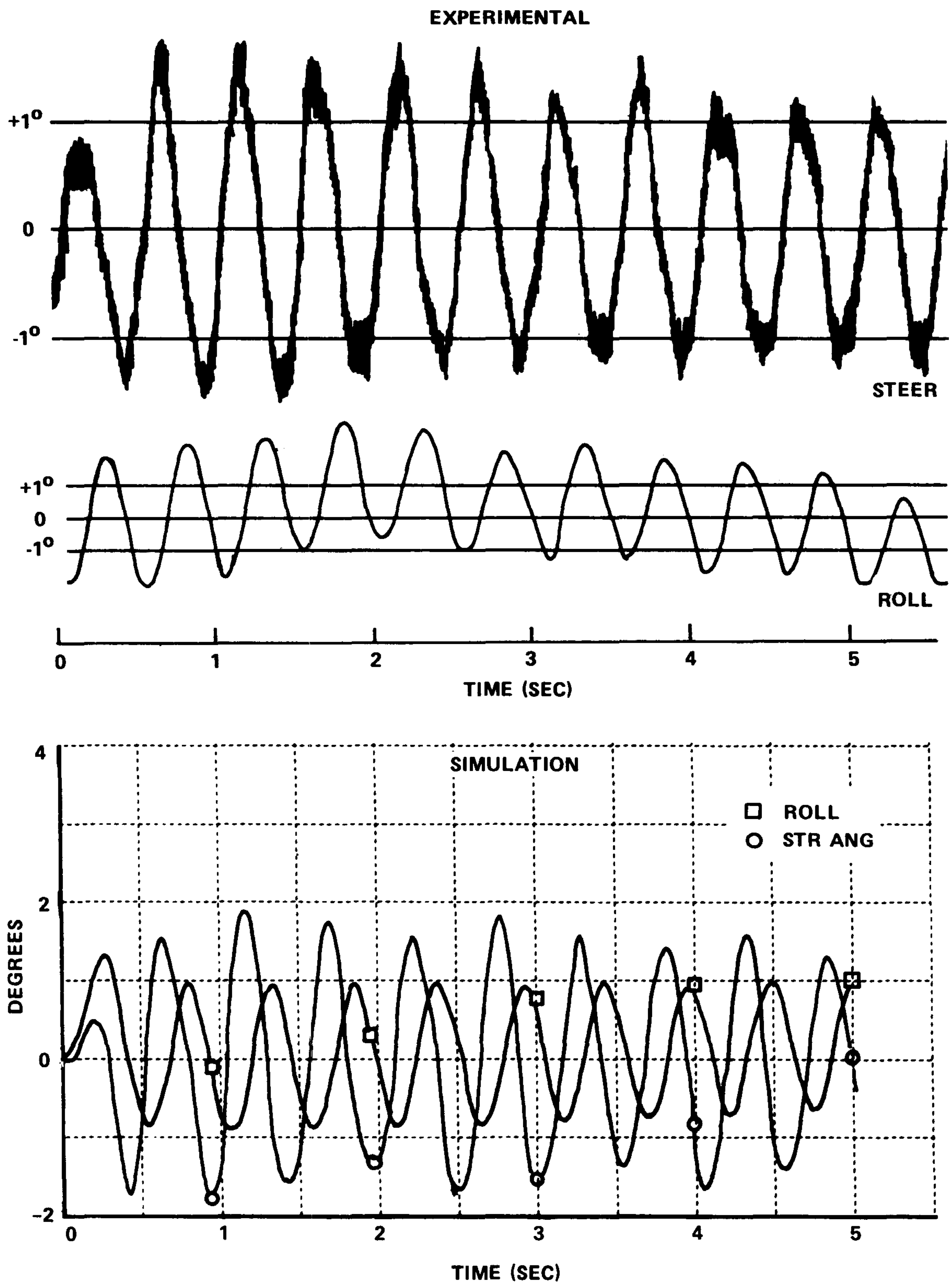

Figure 5. Comparison of Experimental and Simulation Results at 80 mph

Table 1. Results of Simulation Parameter Study

CONFIGURATION OR PARAMETER	VARIATION	NORMALIZED "INITIAL" AMPLITUDE	CONVERGENT OSCILLATION $T_{1/2}$ (sec)	DIVERGENT OSCILLATION T_2 (sec)
STANDARD ELECTRA-GLIDE MOTORCYCLE	70 mph	1.02	3.1	
	80 mph	1.00	21.3	
	87 mph	0.94		28.2
LONGITUDINAL C.G. LOCATION OF TOTAL MOTORCYCLE	MOVED 5 in. FORWARD	0.73	1.3	
	MOVED 2 in. FORWARD	0.88	2.4	
	MOVED 1 in. FORWARD	0.96	4.2	
	MOVED 5 in. REARWARD	1.69		1.4
TOTAL MOTOR CYCLE C.G. HEIGHT	20% HIGHER	0.74	2.6	
	20% LOWER	1.22		32.4
WHEELBASE	12 in. LONGER	1.01	2.8	
	6 in. LONGER	0.99	4.3	
	3 in. LONGER	1.01	6.1	
	12 in. SHORTER	1.25		4.7
TOTAL MOTORCYCLE WEIGHT	20% LESS	1.04	7.2	
	20% MORE	0.94	15.0	
TOTAL MOTORCYCLE YAW INERTIA	20% LESS	0.89	6.3	
	20% MORE	1.06		25.0
TOTAL MOTORCYCLE ROLL INERTIA	20% MORE	0.94	10.2	
	20% LESS	1.04		22.3
FRONT ASSEMBLY C.G. OFFSET FROM STEER AXIS	ZERO OFFSET	0.55	1.1	
	MOVED 0.4 in. FORWARD	0.91	5.8	
	MOVED 0.4 in. REARWARD	1.08		32.8
STEERING HEAD ANGLE	6 deg. MORE	0.69	1.3	
	4 deg. MORE	0.80	1.6	
	2 deg. MORE	0.92	3.1	
	6 deg. LESS	1.34		1.4
STEERING TRAIL	1 in. LESS	0.94	5.8	
	1 in. MORE	1.02	22.9	
FRONT ASSEMBLY STEER INERTIA	20% LESS	0.86	3.6	
	15% LESS	0.92	4.5	
	8% LESS	0.97	6.0	
	20% MORE	1.23		5.1
VISCOUS STEERING DAMPING	20% LESS	0.97	6.9	
	20% MORE	1.04		48.6
FRONT WHEEL SPIN INERTIA	20% MORE	0.76	2.6	
	20% LESS	1.31		4.7
REAR WHEEL PLUS EFFECTIVE ENGINE SPIN INERTIA	ENGINE SPIN DIRECTION REVERSED	0.99	5.8	
	20% LESS	1.00	15.7	
	20% MORE	0.99	17.1	
FRONT TIRE CORNERING COEFFICIENT	10% MORE	1.01	8.7	
	10% LESS	1.07	115.2	
REAR TIRE CORNERING COEFFICIENT	10% MORE	0.99	6.4	
	10% LESS	1.06		124.2
TOTAL FRONTAL AREA	20% LESS	0.99	15.0	
	20% MORE	1.01	19.3	
WINDSHIELD FRONTAL AREA	20% LESS	1.01	15.1	
	20% MORE	0.99	17.0	
IMPROVED CONFIGURATION	—	0.50	1.2	

except two for the standard configuration, were run with initial speeds of 80 mph. Further, the disturbance input for all runs was identical. The results fell into either of two categories; that is, the resultant weave oscillation was either convergent or divergent. Almost without exception these categories reflect either improvement or degradation in weave mode stability since the behavior of the standard configuration at 80 mph was almost perfect limit cycle oscillation (i.e., the time required to damp to half the initial amplitude was over 20 seconds).

The quantitative measures of stability (or instability) are:

(1) $T_{1/2}$ - the time required for the amplitude of the roll angle oscillation to decay to one-half its "initial" amplitude (actually, the amplitude of the second cycle of the roll angle response since this is the first cycle of free oscillation).

(2) T_2 - the time required for the amplitude of the roll angle oscillation to grow to twice its "initial" amplitude.

(3) Normalized "initial" amplitude - the ratio of the "initial" amplitude of the specific configuration to that of the standard configuration at 80 mph.

In interpreting these results, comparisons should be made with the response of the standard configuration at 80 mph, Figure 5. For this run, $T_{1/2}$ was 21.3 seconds. Therefore, large values (greater than about 10 seconds) of $T_{1/2}$ and T_2 indicate that the specific parameter variation had little effect. If the oscillation is convergent, small values ($T_{1/2} < 10$ seconds) are desirable. If divergent, small values ($T_2 < 10$ seconds) are undesirable. Normalized "initial" amplitudes less than 1.0 indicate that the specific configuration was less sensitive to the distrubance input than the standard configuration at 80 mph, and more sensitive for values greater than 1.0.

A second series of runs indicated that significant improvements in weave stability could be achieved using practical design variations with six critical parameters:

(1) Increased front weight distribution,
(2) Longer wheelbase,
(3) Increased rake angle,
(4) Reduced front assembly c.g. offset from steer axis,
(5) Reduced front assembly steer moment of inertia, and
(6) Reduced steering trail.

A final series of runs was aimed at achieving a realistic, improved design using practical combinations of variations of the above six parameters. Figure 6 shows an example of the improved behavior predicted by the simulation using the following modifications to the standard configuration:

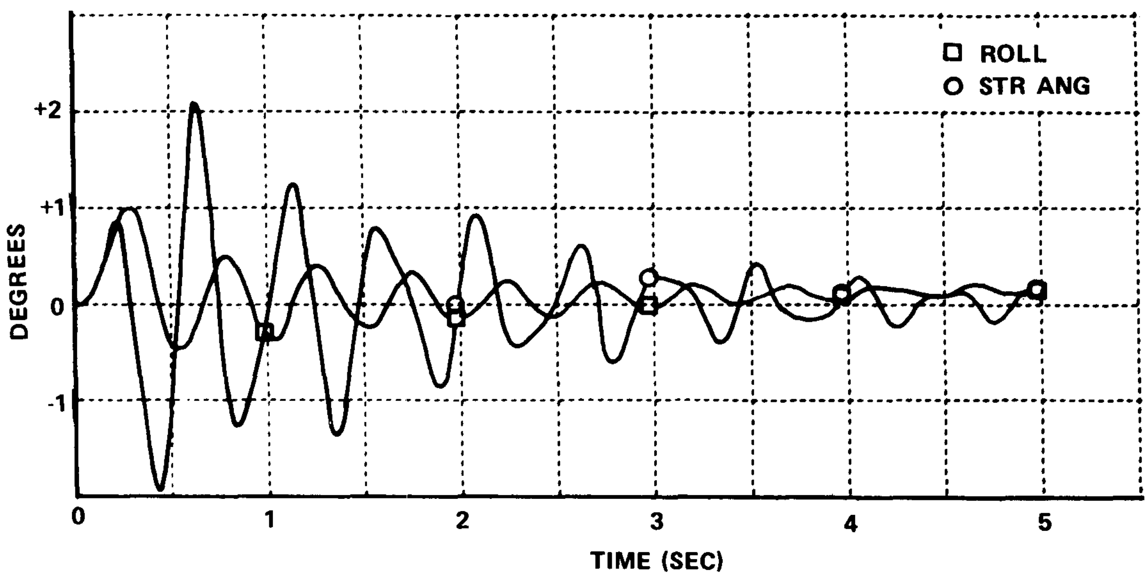

Figure 6 Simulated Response of Improved Configuration at 80 mph

(1) Increasing the front weight distribution from 37.9% to 39.4% (primarily due to lengthening wheelbase),

(2) Lengthening the wheelbase by 1.0 inch,

(3) Increasing the fork rake angle by 2.0 degrees,

(4) Reducing the front assembly c.g. offset from the steer axis to zero,

(5) Reducing the front assembly steer moment of inertia by 15% (primarily due to reducing the front assembly c.g. offset), and

(6) Reducing the steering trail by 0.5 inch.

5. DISCUSSION OF RESULTS

Based on the results of this study, motorcycle parameters can be separated into one of three categories according to their effect on weave behavior at high speed: (1) the effect of the parameter variation was insignificant, (2) the resultant reduction in the stability of other modes of motion or other compromising factors restrict the variation of the parameter, or (3) the effect of the parameter is significant and it is useful in design modifications.

Several parameters were found to have insignificant effects on weave behavior for reasonable ranges of variation of a specific configuration. These parameters include the windshield and body aerodynamic factors, the front and rear tire cornering coefficients, the rear wheel spin inertia, the total mass, and the total roll and yaw moments of inertia.

Certain design variations would appear to be desirable for improving weave behavior, but such changes have other adverse effects. The simulation results indicate that a higher motorcycle c.g. would increase weave damping as well as reduce the sensitivity to disturbances. However, it is generally accepted that a low c.g. is desirable for good handling performance. Increasing front wheel spin inertia would appear to be effective; however, this realistically cannot be accomplished without increasing the front assembly steer inertia which significantly degrades weave behavior. Certain configurations significantly reduced the damping of the wobble mode of oscillation (about 4 Hz. for this motorcycle). Of particular interest is the increased tendency to wobble caused by reduced steering trail and reduced front assembly c.g. offset from the steer axis.

Practical design variations of six parameters showed significant reductions in the tendency to weave. As discussed previously, these include weight distribution, wheelbase, front assembly geometry (rake and trail), and front assembly inertia properties (steer, moment of inertia, and c.g. offset). The most critical of these design variations appears to be weight distribution. Increasing weight distribution to the front by a few percent effectively damps the weave oscillation without adversely affecting other modes of motion.

There were indications from this study that a particular parameter variation can have opposite effects at the same speed, depending on the base motorcycle configuration. The results of Sharp showed that opposite effects can occur, depending on the speed of operation. Thus, as concluded by Weir regarding motorcycle handling, the weaving behavior of a motorcycle is also the result of a sensitive combination of many design (and operational) parameters. Therefore, the most practical improved motorcycle design will consist of a coordinated set of modifications involving small changes in several critical parameters. Such a design can eliminate the weave oscillation from the operating speed range without increasing the tendency to wobble or adversely affecting handling performance.

Several parameters which are unimportant for design improvements should not be neglected as operational factors. Reduced tire cornering coefficients are not highly significant at the 10% variation level. However, a much greater reduction in cornering coefficient as occurs with very low inflation pressure could cause an unstable weave oscillation. The effects of steering damping should be carefully observed. Small variations in other parameters may be difficult to achieve, but relatively large increases in steering damping may occur with normal use and/or lack of maintenance. The 20% variation in steering damping is probably not representative of the magnitude of changes which occur under actual operating conditions. Although the effect of a 20% increase is small, realistic extreme variations could result in a significant reduction in weave damping. It should also be recognized that the addition of heavy luggage loads on the rear of the motorcycle has a particularly adverse effect on weave behavior as it increases rear weight bias, total weight and total yaw moment of inertia; all of which have been shown to reduce weave mode damping.

The objective of this study was to determine what changes could be made in the design of a motorcycle to prevent high speed weave instability. Several critical design parameters have been identified and their effects quantitatively determined. Further work is needed to properly determine the effects of the critical operational factors.

6. ACKNOWLEDGEMENTS

The author is grateful to the Harley-Davidson Motor Company, Inc. for supporting this research program and permitting the presentation here of the results, and to the Dunlop Tire and Rubber Corporation for providing the data on motorcycle tires. The author also appreciates the valuable technical assistance of Raymond J. Miennert and Michael J. Baxter of Harley-Davidson Motor Company and is particularly indebted to Dennis T. Kunkel and Roy S. Rice of Calspan Corporation for their comments, suggestions, and assistance regarding the development and use of the simulation and for their review of the manuscript of this paper.

7. BIBLIOGRAPHY

1. Bower, George S., "Steering and Stability of Single-Track Vehicles," The Automobile Engineer, Vol. V, pp 280-283, 1915.

2. Collins, Rober Neil, "A Mathematical Analysis of the Stability of Two-Wheeled Vehicles," Ph.D. Thesis, University of Wisconsin, 1963.

3. Dohring, E., "Stability of Single-Track Vehicles," Forschung Ing. Wes. 21, No. 2, pp. 50-62, 1955 (translation by Cornell Aeronautical Laboratory, Inc., 1957).

4. Dohring, E., "Steering Wobble in Single-Track Vehicles," Automob. techn. z., Vol. 58, No. 10, p. 282-286 (M.I.R.A. Translation No. 62167).

5. Fu, Hiroyasu, "Fundamental Characteristics of Single-Track Vehicles in Steady Turning," Bulletin of JSME, Vol. 9, No. 34, pp. 284-293, 1965.

6. Kageyama, Katumi, Fu, Hiroyasu, and Kosa, Fumio, "Experimental Study on the Standing Stability of the Motorcycle," Bulletin of JSME, Vol. 5, No. 17, pp. 202-209, 1962.

7. Manning, J.R., "The Dynamical Stability of Bicycles," Department of Scientific and Industrial Research, Road Research Laboratory, Note No. RN/1605/JRM, July 1951.

8. Pearsall, R.H., "The Stability of the Bicycle," Proc. Inst. Automobile Eng., Vol. XVII, p. 395, 1922.

9. Rice, R.S. and Roland, R.D., "An Evaluation of the Performance and Handling Qualities of Bicycles," Calspan Report No. VJ-2888-K, prepared for the National Commission on Product Safety, 1970.

10. Roland, R.D. and Massing, D.E., "A Digital Computer Simulation of Bicycle Dynamics," Calspan Report No. YA-3063-K-1, prepared for the Schwinn Bicycle Company, June 1971.

11. Roland, R.D. and Lynch, J.P., "Bicycle Dynamics, Tire Characteristics and Rider Modeling," Calspan Report No. YA-3063-K-2, prepared for the Schwinn Bicycle Company, March 1972.

12. Roland, R.D. and Rice, R.S., "Bicycle Dynamics Rider Guidance Modeling and Disturbance Response," Calspan Report No. ZS-5157-K-1, prepared for the Schwinn Bicycle Company, April 1973.

13. Roland, R.D. and Kunkel, D.T., "Motorcycle Dynamics, The Effects of Design on High Speed Weave," Calspan Report No. ZN-5259-K-1, prepared for the Harley-Davidson Motor Company, Inc., May 1973.

14. Sharp, R.S., "The Stability and Control of Motorcycles," J. Mech. Engrg. Sci., Vol. 13, No. 4, August 1971.

15. Singh, Digvijai V., "Advanced Concepts of the Stability of Two-Wheeled Vehicles," Application of Mathematical Analysis to Actual Vehicles," Ph.D. Thesis, University of Wisconsin, 1964.

16. Singh, D.V. and Goel, V.K., "Stability of Rajdoot Scooter," Paper No. 710273, SAE Automotive Engineering Congress, January 1971.

17. Weir, D.M., "Motorcycle Handling Dynamics and Rider Control and the Effect of Design Configuration on Response and Performance," University of California, Los Angeles, 1972.

18. Wilson-Jones, R.A., "Steering and Stability of Single-Track Vehicles," Proceedings of the Institution of Mechanical Engineers, Automobile Division, London, 1951-52.

19. Wipple, F.J.W., "The Stability of the Motion of a Bicycle," Quarterly Journal of Pure and Applied Math., Vol. 30, No. 120, pp. 312-348, 1899.