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AN EVALUATION OF THE SAFETY PERFORMANCE OF TRICYCLES AND MINIBIKES

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FOREWORD

This report covers the work performed by Calspan Corporation for the Bureau of Product Safety (BPS) of the Food and Drug Administration (FDA) under Contract No. FDA 72-91 during the period from 1 May 1972 to 30 September 1972. The program was conducted under the guidance of Mr. Carl Blechschmidt of the Children's Hazard Division. The study was performed at Calspan by the Vehical Research Department.

The authors gratefully acknowledge the assistance of their co-workers at Calspan who contributed to the many and varied tasks of the study. In particular, thanks are due to Mr. Donald W. Hess for his patient care in making the voluminous measurements of the test units and to Mr. Douglas Milliken for his willingness to operate the minibikes under all conditions.

ABSTRACT

Evaluations of the stability and performance characteristics of minibikes and children's tricycles have been made in order to identify those design and operational qualitites which may be contributory to injury-causing accidents with these types of vehicles. Both experimental and analytical methods have been applied in this study. Several representative examples of both minibikes and tricycles were obtained to provide baseline design and performance information. The pertinent physical characteristics of all units were measured prior to performing a variety of full-scale stability and maneuvering capability tests on each vehicle. Tricycle studies were aimed primarily at defining the operational conditions at which rollover could occur. The influences of geometrical design, rider weight, speed, and applied steering were considered in the development of a rollover stability parameter which would be applicable in formulating a safety standard. Extensive tests were performed with the minibikes (minicycles) in order to measure the capabilities of the machines and to identify situations in which rider safety could be compromised. For these units, design concepts and operating modes which are related to stability in the pitch plane were found to be significant. A brief design parameter variation study utilizing a nonlinear simulation of the minibike was performed to identify the more influential design characteristics in providing sat-

ABSTRACT (Cont.)

isfactory lateral motion response. All results are evaluated in terms of potential safety standards and recommendations on which the FDA might base such standards are offered.

SUMMARY OF RESULTS AND CONCLUSIONS

The major results and conclusions of this study are:

Tricycles

1. Performance of units for children in the 2-6 years age bracket is marked by speed in the range of 4 to 7 miles/hour, unrestricted steering for all practical purposes (i.e., greater than 90 degrees), and seat height to rear track ratios of approximately one (for conventional units).
2. These combinations of design and operational characteristics result in a stability pattern for conventional tricycles which is generally satisfactory with respect to pitchover for the single rider but is inadequate with respect to rollover (tipover) in normal play.
3. It is recommended that the Bureau of Product Safety consider safety standards covering rollover stability, seat height adjustibility, limited steering angle, and removal of the rear step bar to discourage double riding.

Minibikes

4. Performance of six representative units as measured in an extensive experimental program may be characterized by maximum speeds of 25 miles/hour, braking decelerations of at least .5g, tractive accelerations in the range of

SUMMARY OF RESULTS AND CONCLUSIONS (Cont.)

.2 g.

5. Potential problem areas concerned with inadvertent acceleration "wheelies", pitch and bounce stability over uneven terrain, braking control nonlinearities, and cornering limitations because of structural elements contacting the ground were observed.
6. Recommendations for consideration in Bureau of Product Safety standards cover braking, suspension, cornering, and acceleration characteristics.

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1.0 INTRODUCTION

The United States is very clearly a nation on wheels. From the toddler on his velocipede to the affluent adult in his super-powered automobile, the demand for mobility is a continuing one throughout the country whether it be for recreational or utilitarian purposes. It is not surprising therefore that wheeled vehicular toys are among the most popular with children. The fact that they are so popular (i.e., nearly every youngster has a tricycle) and that they receive a great deal of use by their owners is the foundation for concern about their safety of operation. Based on its observations of accident reports, the Bureau of Product Safety (BPS) of the Food and Drug Administration (FDA) has selected the <u>tricycle</u> - the traditional three - wheeler ridden by millions of children up to the age of six - and the <u>minibike</u> - the mechanically - powered small two - wheeler for evaluation of safety of performance. Approximately 100,000 children are injured each year in tricycle accidents. Another 70,000 are injured in mini-bike accidents. These injuries indicate that carelessness and lack of parental supervision are not the only causes of childhood injury relating to these vehicles. These figures indicate that design improvements can reduce the possibility of a child's being injured. This report describes the results of a program performed by Calspan on this subject.

The objective of this program is to interrelate the significant variables that can be used to both predict performance and establish safety standards for stability and performance of two and three-wheeled vehicular toys, especially tricycles and minibikes. the variables of interest are thoses associated with vehicle design, with the rider and with the riding situation.

The report treats the two types of vehicles separately. Following this introduction, the evaluation of tricycles, utilizing both experimental and analytical methods, is covered in Section 2.0. A similar discussion of the minibike studies is given in Section 3.0. In section 4.0, the relationship of the results of this work to the formulation of safety standards dealing with the stability and performance of these vehicles is discussed and recommendations are presented. References are listed in Section 5.0. Several appendices, which treat the analyses in more detail than is given in the main body of report, are attached.

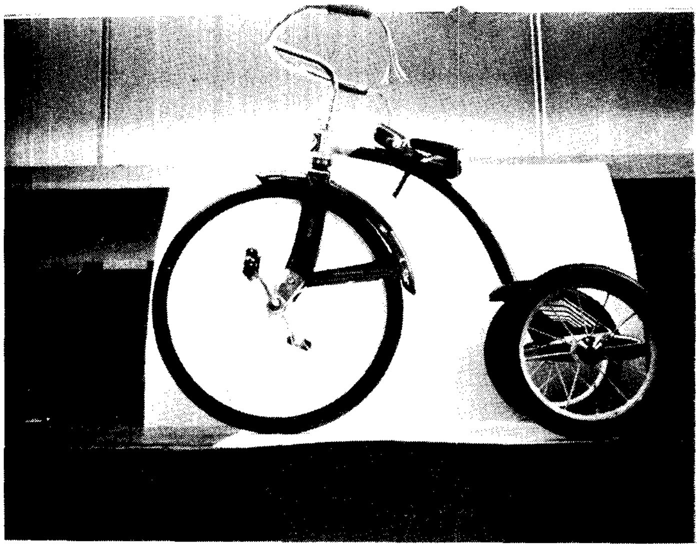
2.0 TRICYCLES

This section covers the results of the tricycle studies. Six representative units, believed to provide a good cross section of three-wheeled vehicles for test and measurement purposes, were obtained. Photographs of these test units are shown in Figure 1 and their principal physical characteristics, as measured at CAL, are listed in Table 1. Full scale performance test results, to determine practical ranges for the operational variables (speed and steering angles), are given in Table 2.

2.1 Rollover Stability

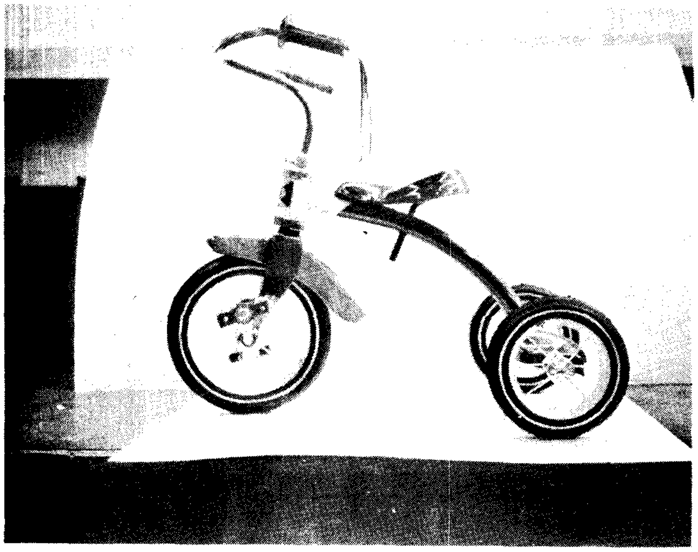
The measured physical charcteristics of the test units were combined with rider characteristics to compute values of critical operating parameters (e.g., the longitudinal and vertical location of the system center-of-gravity) as listed in Table 3 for a range of rider weights. The method of calculation is described in Appendix A. In turn, these values were used to compute values of a <u>stability parameter</u> (a metric which combines rider and vehicle characteristics) for each configuration which can be compared to a <u>stability boundary curve</u> (which involves operational characteristics) to evaluate susceptibility to tip over.

The rollover stability characteristics of the test units are shown in Figure 2 where operating velocity is plotted against a stability parameter as a function of steering angle. The stability parameter is defined as -



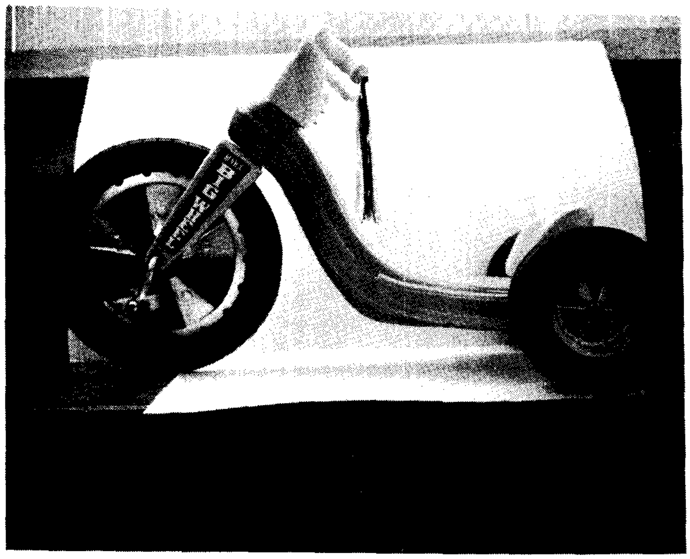
20 INCH
TRICYCLE

14 INCH
TRICYCLE

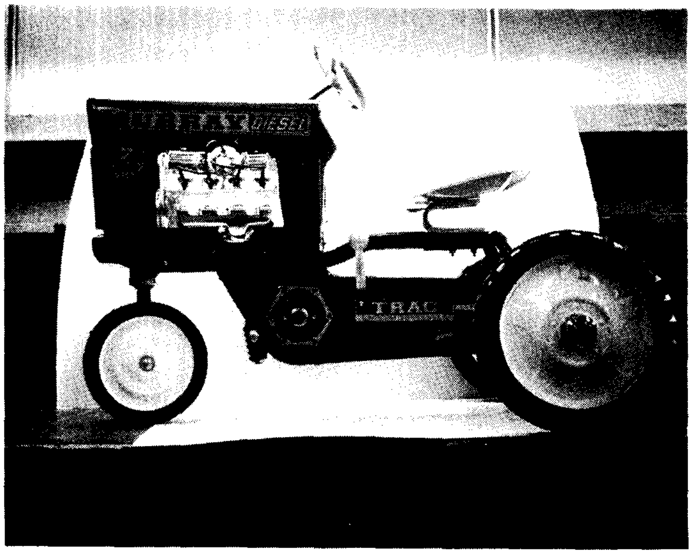


10 INCH
TRICYCLE

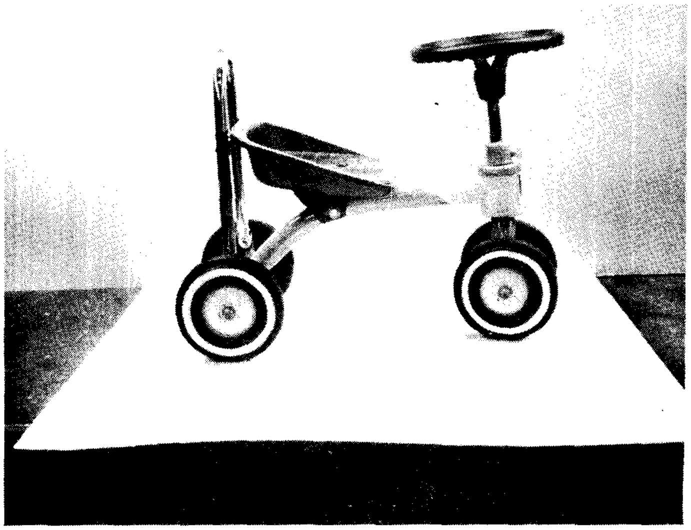
Figure 1a TEST UNITS (TRICYCLES)



UNDERSLUNG



TRACTOR



VELOCIPEDE

Figure 1b TEST UNITS (TRICYCLES)

Table 1
TRICYCLE PHYSICAL CHARACTERISTICS

	WHEELBASE (in)	REAR TRACK (in.)	FRONT TRACK (in.)	STEP HEIGHT (in.)	SEAT POST LOCATION* (in.)	SEAT HEIGHT		PEDAL CRANK DIAMETER (in.)	WEIGHT (lbs)			LONG c.g. (FROM FRONT WHEEL) (in.)	VERT. c.g. (FROM GROUND) (in.)
						MAX.	MIN.		FRONT	REAR	TOTAL		
VELOCIPEDE	13.5	9.0	5.5	–	4.7	8.4	–	–	2.7	2.5	5.2	5.2	6.9
10 in. TRICYCLE	16.6	15.5	–	3.6	5.3	14.5	13.0	3.4	7.2	5.6	12.8	7.3	9.3
14 in. TRICYCLE	19.9	18.6	–	5.1	8.3	19.0	16.9	4.5	8.2	8.0	16.2	9.8	9.5
20 in. TRICYCLE	21.5	19.5	–	6.3 10.9	9.3	23.5	21.8	5.5	11.9	12.2	24.1	10.9	11.8
UNDERSLUNG	26.5	20.5	–	–	3.5	5.7	–	5.25	6.5	6.1	12.6	12.9	8.5
TRACTOR	27.3	20.8	4.0	7.1	5.8	15.0	–	6.0	15.3	20.0	35.3	15.5	9.8

*HORIZONTAL DISTANCE FROM REAR AXLE CENTERLINE TO TOP OF SEAT POST'

Table 2
TRICYCLE PERFORMANCE CHARACTERISTICS

	MAX. STRAIGHT SPEED (MPH) (1)	STRAIGHT SPEED AT 60 RPM AT PEDAL CRANK(2)	AVAILABLE STEERING MOTION FREEDOM (deg)(1)	RADIUS OF TURN WITH 30° STEER ANGLE(1)	ABLE TO CLIMB 1½ in. OBSTACLE WITH ONE REAR WHEEL(1)	OBSERVED TENDENCY TO TIP OVER IN NORMAL PLAY
VELOCIPEDE	–	–	±35	1.9	–	–
10 in. TRICYCLE	4.7	1.7	UNLIMITED	2.7	NO	–
14 in. TRICYCLE	6.5	2.5	±85	3.0	YES	MARKED
20 in. TRICYCLE	6.5	3.5	UNLIMITED	3.3	YES	MARKED
UNDERSLUNG	6.0	2.8	UNLIMITED	–	YES	NONE
TRACTOR	6.0	3.0	UNLIMITED	–	YES	NONE

(1)MEASURED
(2)COMPUTED

Table 3

COMPUTED CENTERS-OF-GRAVITY FOR TEST UNITS (RIDER ONLY)

TEST UNIT	RIDER WEIGHT (lbs.)	LONG.c.g. A (in.)	VERT. c.g. h (in.)	A/h	ℓ - A (in.)	$\frac{\ell - A}{h}$
10 in. TRICYCLE	30	10.5	18.2	0.58	5.1	0.28
	40	10.7	18.9	0.59	4.9	0.26
14 in. TRICYCLE	30	10.95	20.2	0.54	8.95	0.45
	40	11.05	21.3	0.52	8.85	0.42
	50	11.1	22.0	0.50	8.8	0.40
20 in. TRICYCLE	30	11.6	22.3	0.52	10.9	0.49
	40	11.7	23.7	0.49	10.8	0.46
	50	11.75	24.75	0.48	10.75	0.43
	60	11.8	25.3	0.47	10.7	0.42
UNDERSLUNG	30	20.0	13.5	1.48	6.5	0.48
	40	20.6	14.0	1.47	5.9	0.42
	50	21.0	14.2	1.47	5.5	0.39
	60	21.2	14.4	1.47	5.3	0.37
VELOCIPEDE	30	8.5	14.9	0.57	5.0	0.34
TRACTOR	30	18.3	15.8	1.16	9.0	0.57
	40	18.7	16.8	1.11	8.6	0.51
	50	19.1	17.5	1.09	8.2	0.47
	60	19.3	18.1	1.07	8.0	0.44

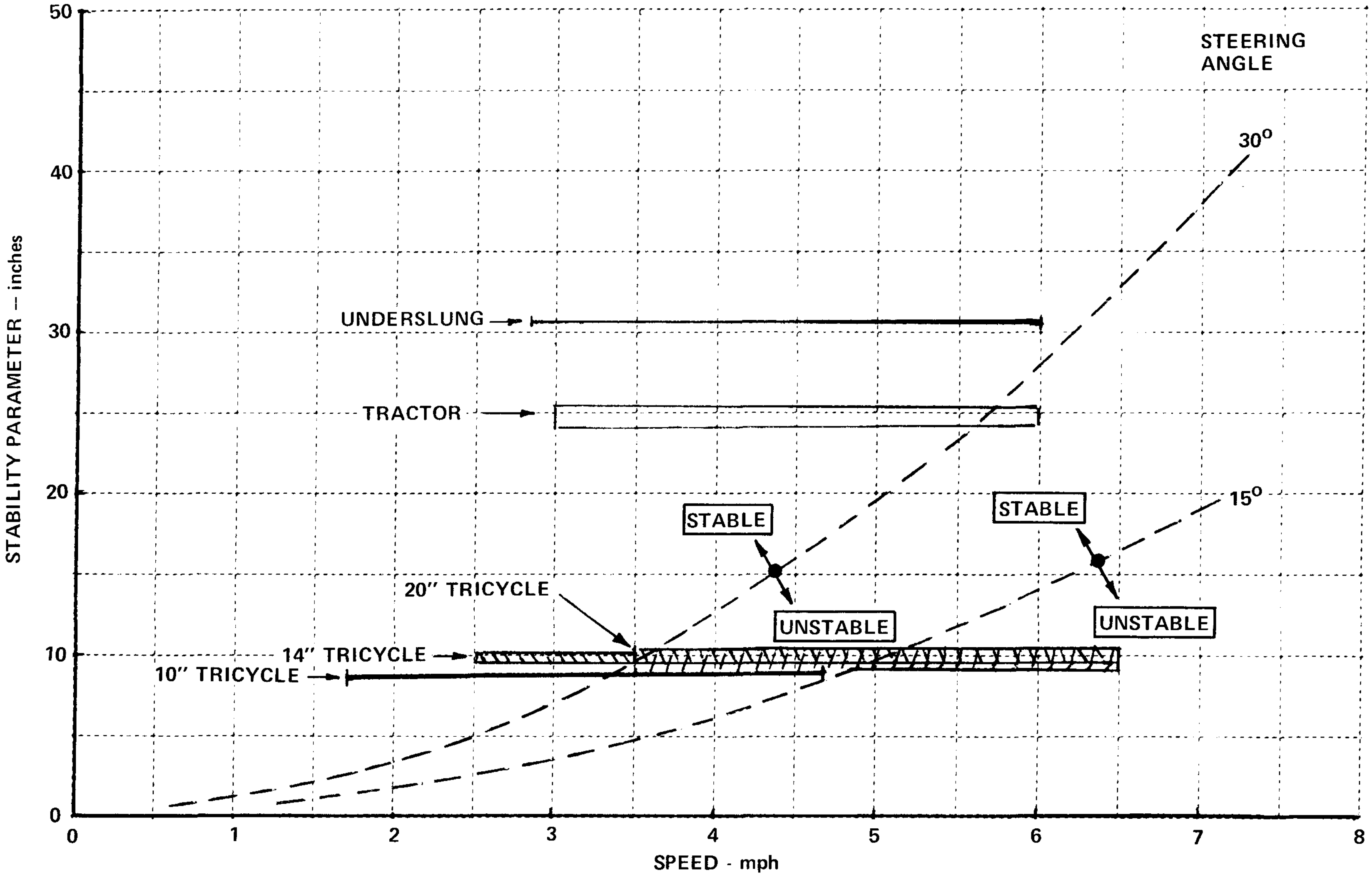


Figure 2 ROLLOVER STABILITY BOUNDARY

$$\frac{aT}{h} \qquad \text{for three-wheeled units}$$

and

$$\frac{aT}{h} + \frac{t}{h}(\ell - a) \qquad \text{for four-wheeled units}$$

where

a: the horizontal distance from the front wheel contact point to the center-of-gravity of the tricycle-rider system

T: overall width of the tricycle at the rear axle (rear track)

h: the vertical distance from the ground to the center-of-gravity of the tricycle-rider system

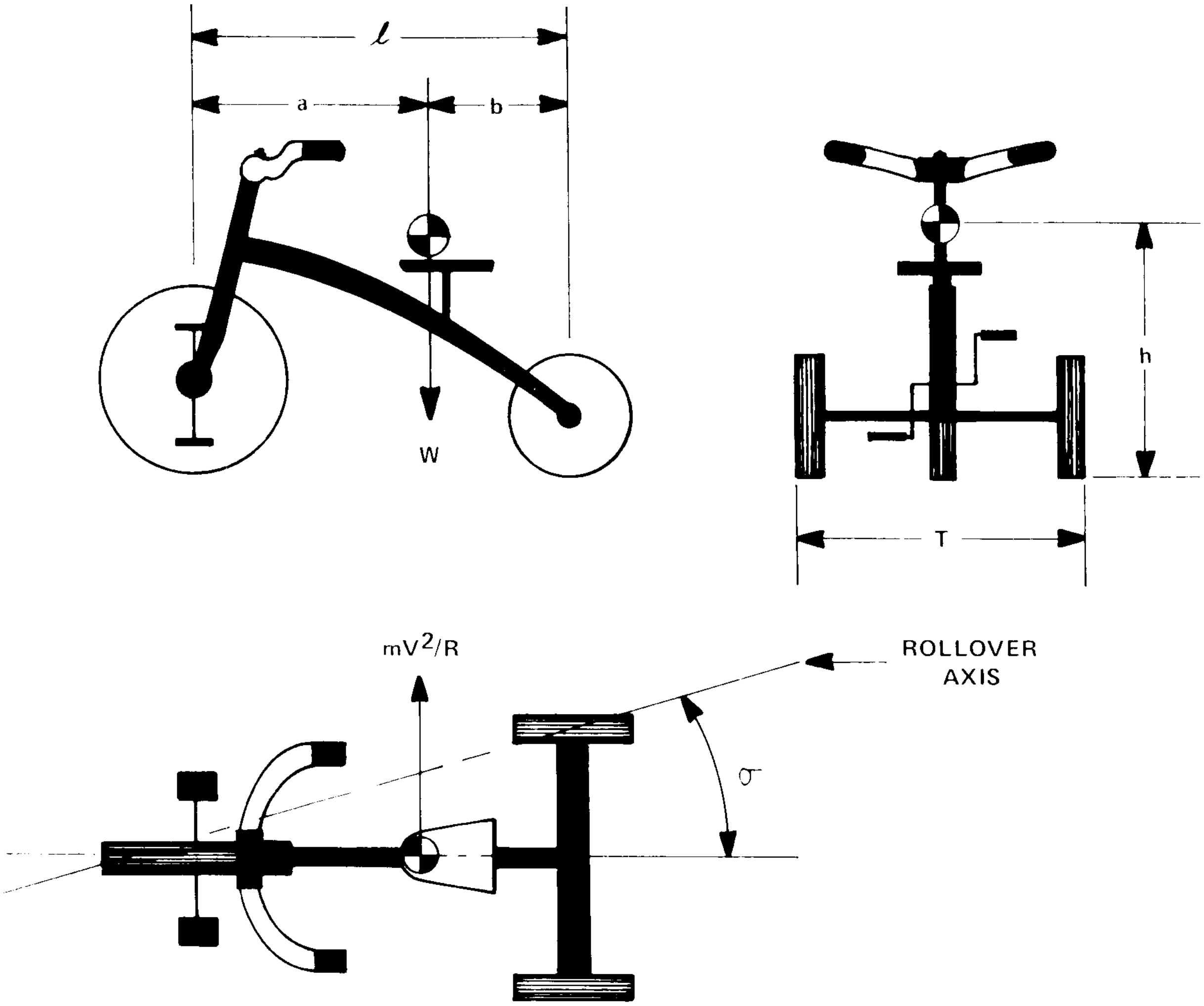
t: overall width of the unit at the front axle (front track)

ℓ: wheelbase

(See Figure 3)

This stability parameter contains vehicle design and rider terms only; as shown in Appendix A, it is developed from a moment balance expression which relates the design characteristics to the operationsl terms. That is, the value of aT/h should be greater than $\frac{2V^2\delta}{g}$ (where V is velocity, δ is steering wheel angle, and g is the gravitational constant - all in appropriate dimensions).

This stability parameter is a convenient form for defining operational boundaries beyond which the unit may rollover. It should be clearly understood that the boundary curves illus-



R = RADIUS OF TURN
UPSETTING FORCE: $m\,V^2/R$
RESTORING FORCE: $W = mg$

Figure 3 CHARACTERISTIC DIMENSIONS OF TRICYCLE MODEL trated in Figure 2 have been computed for special sets of conditions (selected rider weights and statures) in order to demonstrate the utility of this approach in specifying stability requirements and in identifying the tricycle design characteristics which are pertinent to rollover stability. These computations have not been quantitatively supported with full-scale testing since the performance of such tests without elaborate precautions is of itself unsafe. But, observations made during the test program (Figures 4 and 5) provided solid evidence that the tricycles of conventional design (the 10, 14, and 20 inch units) could be rolled over in the normal region of operation whereas the tractor and the low-slung unit could not. Thus, the stability analysis has allowed us to identify the significant elements of the problem - vertical and longitudinal location of the center-of-gravity as influenced by rider weight , wheelbase and seat location; rear track; speed, and steering angle. Additional considerations regarding the use of the stability parameter are listed below.

1. The available steering angles on the units which were tested in this program were shown in Table 2. The fact of availability does not imply utility however. Steering motion is restricted by the rider's body (i.e., the handlebar is turned into the body) and by arm length. To put steering motion requirements into perspective, we might consider the steering angle required to negotiate a 5 ft. radius arc. For a wheelbase of 20 inches, this angle is only .33 radian or about 19 degrees. Therefore, the

Figure 4 TRICYCLE CORNERING

[NOTE SLIGHT WHEEL LIFT EVEN WITH THESE LOW STEERING ANGLES. ALSO NOTE HOW RIDER LEANS IN TO HELP STABILITY IN RIGHT HAND PHOTOGRAPH.]

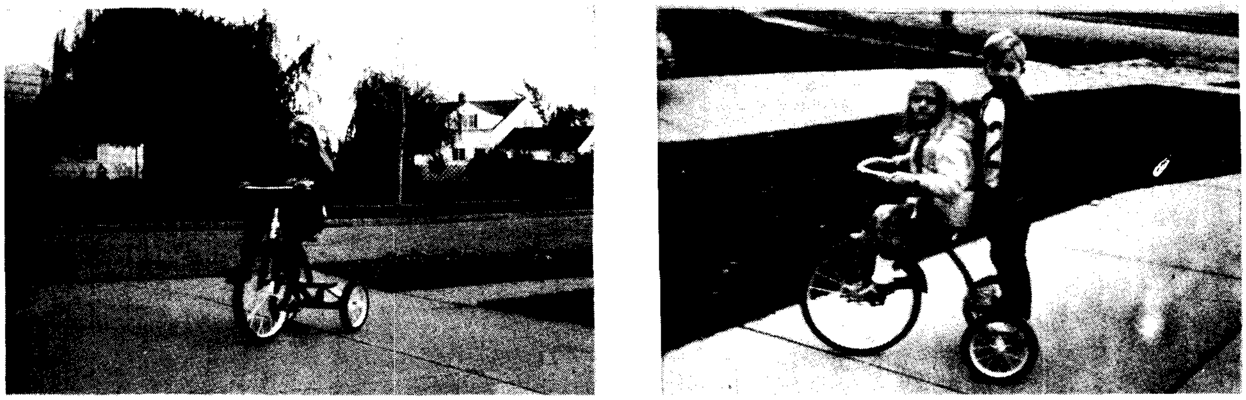


Figure 5 TYPICAL TRICYCLE PLAY

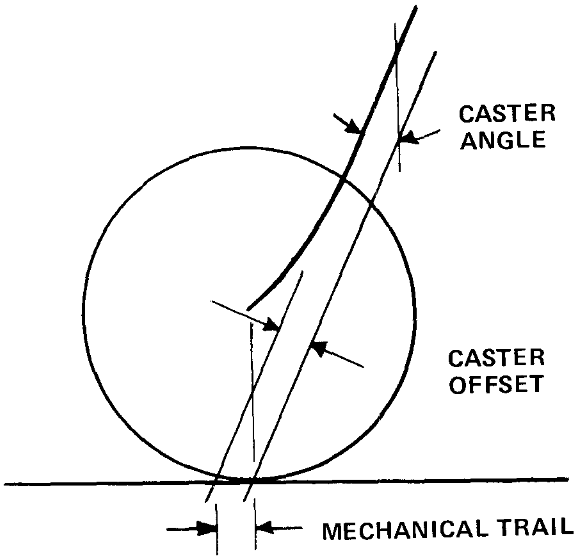
[LEFT PHOTOGRAPH SHOWS A MODERATE CORNERING MANEUVER. RIGHT PHOTOGRAPH ILLUSTRATES DOUBLE -RIDING.]

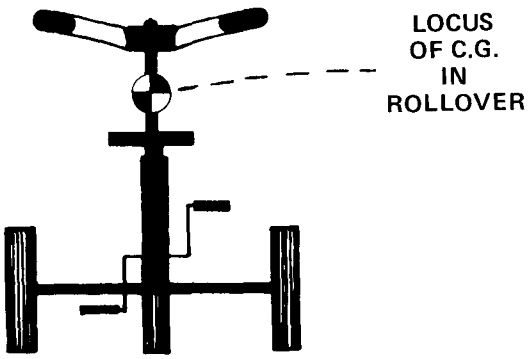
stability boundary curves are shown for steering angle inputs of 15 and 30 degrees.

2. Each vehicle is represented on the stability plot by a bar extending between two values of speed. The lower value is based on the computed speed of the unit when pedaled at a crank rate of 60 rpm. This rotational velocity is generally considered to be a comfortable rate. The higher value is the maximum speed attained by a five year old, 40 pound girl in actual tests. All units are stable at speeds lower than that indicated by the left edge of the bar. All are seen to be stable at the "comfortable speed" but the larger conventional designs are susceptable to rollover at higher speed, even with small steering inputs.

3. The effect of rider leaning is not accounted for in the equations. Two counteracting influences are present - the rider can lean into the turn in an effort to maintain the system center-of-gravity inside the rollover axis, but this action is inhibited in part by the presence of the rotated handle bars. Clearly, if the rider leans outward (i.e., moves with the handle bars) the stability problem is worsened.

4. Most tricycle designs utilize very small values of caster offset (identified in the accompanying sketch) and, therefore, the change in the orientation of the rollover axis with steering angle has been neglected. This effect, if it is present to any significant degree, may be either advantageous or detrimental to stability, depending on the relative locations of the





point of intersection of steer axis with the ground and the front wheel contact point.

5. In developing the limiting stability equation, transient dynamics have been ignored. In effect, the stability inequality states that if a net destabilizing moment exists, the tricycle will eventually roll over if the condition is unchanged. Two effects (again conflicting) are present. On the one hand, energy must be added to the system in order to raise the c.g. above the rollover axis. This is shown in the above sketch. The required energy is supplied by the destabilizing moment acting required energy is suppled by the destablizing moment acting over a period of time. On the other hand, the net moment

is increasing throughout this period because the upsetting moment arm (h) is increasing while the restoring moment arm (initially, a sinσ) is decreasing. (See Figure 3)

6. The effect of rider weight on the value of the performance parameter is seen to be relatively small. This is due to simultaneous increase in both the upsetting moment and the restoring moment; although the vertical center-of-gravity of the rider-tricycle system increases with increased rider weight, this is to a large degree compensated by a rearward shift of the c.g. For example, an increase in rider weight of 100% (from 30 to 60 pounds) on the 20-inch tricycle decreases the value of the stability parameter by only about 10%.

Unfortunately, increased rider weight and increased seat height tend to occur together; as the child grows, his increased leg length is accomodated by raising the seat. The stability problem is thereby compounded (the system c.g. height is increased because greater weight is located higher above the ground) and is mitigated only in those designs in which the seat is also moved aft as it is elevated. Most currently available units incorporate this feature.

7. Cross-slope riding and turning on grades represent operating conditions which, under some circumstances, contribute additional destabilizing rollover moments to the rider-tricycle combination. The same tricycle design characterisitcs are involved as in turning on a level surface (i.e., a low center-of-

gravity and a wide rear track are desirable) so the principal effect of riding on a slope is to decrease the size of the safe-operation envelope. Turns must be made at lower speeds and/or smaller steering displacements must be used to stay within this envelope.

2.2 Pitchover Stability

Stability parameters characterizing limiting motions in the pitch plane of the tricycle, similar to the rollover parameter, can also be devised. As developed in Appendix B, the pertinent expressions for stability in the pitch degree of freedom are:

$$\tan\theta_F = a/h$$

$$\tan\theta_R = b/h$$

where θ_F and θ_R are downhill and uphill grade angles and a, b, and h are as previously defined.

These equations indicate that the tricycle <u>will not</u> pitch over on grades with slopes less than θ_F or θ_R.

Values of a/h and b/h for the test units were previously given in Table 3. They have been converted in Table 4 to the limiting values of the angles of slopes for which pitch stability is maintained. It can be seen that rider-only pitch stability is not a problem with the test units - all are acceptable on slopes of about 15 degrees or greater for all rider weights, Although the rearward pitchover parameter is more sensitive to rider weight than is the rollover parameter, adequate margin is

Table 4
CRITICAL SLOPE ANGLES FOR PITCHOVER

	CRITICAL SLOPE ANGLES			
	RIDER-ONLY		DOUBLE-RIDING	
TEST UNIT	θ_F	θ_R	θ_F	θ_R
VELOCIPEDE				
30 lb. RIDER	30.0	19.0	–	–
10 in. TRICYCLE				
30 lb. RIDER	30.0	15.5	31.0	7.5
40 lb. RIDER	30.5	14.5	30.0	9.0
14 in. TRICYCLE				
30 lb. RIDER	28.5	24.0	32.0	11.0
40 lb. RIDER	27.5	23.0	31.0	12.0
50 lb. RIDER	26.5	22.0	30.5	12.5
20 in. TRICYCLE				
30 lb. RIDER	27.5	26.0	31.5	12.5
40 lb. RIDER	26.0	24.5	30.5	13.0
50 lb. RIDER	25.5	23.5	30.0	13.5
60 lb. RIDER	25.0	23.0	29.0	14.0
UNDERSLUNG				
30 lb. RIDER	56.0	25.5	–	–
40 lb. RIDER	56.0	23.0	–	–
50 lb. RIDER	56.0	21.5	–	–
60 lb. RIDER	56.0	20.5	–	–
TRACTOR				
30 lb. RIDER	49.0	30.0	–	–
40 lb. RIDER	48.0	27.0		
50 lb. RIDER	47.5	25.0		
60 lb. RIDER	47.0	24.0		

margin is available at all reasonable operating conditions.

2.3 Other Operational Considerations

In addition to the fundamental stability characteristics in the roll and pitch degrees of freedom previously discussed, operational safety of tricycles depends upon appropriate attention to a number of other factors concerned with design and usage. A portion of this study was therefore devoted to examination of the interaction of these factors with safe operation. These considerations are discussed below.

Passenger Effect

Several of the test vehicles incorporate steps over the rear axles. Such designs invite the use of these steps for carrying a passenger, as shown in Figure 5 . Computations of the effect of the passenger on the value of the stability parameter for the three conventional-design tricycles were made for the condition of a 40 lb. passenger. It was assumed that this weight is centered over the rear axle with the passenger in a standing position except for the case of the higher step on the 20 inch unit.

For computation purposes, a fixed height for the c.g. of 24 inches is used to determine the location of the system's center-of-gravity. Coupled with the computations shown in Table 3 for the rider-only configurations, modified values for the rider-passenger condition as shown in Table 5 can be calculated using the method described in Appendix C. The effect of the passenger is to raise the c.g. and to move it toward the rear. If values of a'/h' as given in Table 5 are compared with values of a/h taken from Table 3, it can be seen that the trend is toward increased rollover stability although the effect is not large. On the other hand, comparisons of values of b/h for the two conditions show a marked loss in rearward pitchover stability. (Table 4) In addition, it is possible for the passenger to the system center-of-gravity even further to the rear by flexing at the knees or hips (as shown in Figure 6).

Figure 6 INCREASED REAR PITCHOVER MOMENT

Table 5

COMPUTED CENTERS-OF-GRAVITY FOR CONVENTIONAL TRICYCLES (DOUBLE-RIDING)

TEST UNIT	RIDER WEIGHT (lbs)	A′ (in.)	h′ (in.)	A′/h′	b′ (in.)	b′/h′
10 in. TRICYCLE	30	13.5	22.7	0.50	3.1	0.136
	40	13.2	22.7	0.58	3.5	0.154
14 in. TRICYCLE	30	15.1	24.3	0.62	4.6	0.189
	40	14.7	24.6	0.60	5.2	0.212
	50	14.4	24.6	0.585	5.5	0.224
20 in. TRICYCLE (LOWER STEP)	30	15.8	25.7	0.615	5.7	0.222
	40	15.4	26.2	0.59	6.1	0.232
	50	15.1	26.6	0.57	6.4	0.240
	60	14.9	26.8	0.555	6.6	0.246
20 in. TRICYCLE (UPPER STEP)	30	13.7	27.7	0.495	7.8	0.282
	40	13.5	28.0	0.485	8.0	0.286
	50	13.4	28.3	0.475	8.1	0.286
	60	13.3	28.4	0.47	8.2	0.290

Pedal crank and pedals

A condition which shows up in a significant number of tricycle accident cases is the rider's foot slipping from the pedal. Several factors can contribute to this situation.

- Pedal material - the use of a material on the pedal which provides a high coefficient of friction with most shoe sole materials should be a regulated responsibility of the manufacturer. Furthermore, designs which emphasize pedal integrity and/or render the tricycle inoperable if the pedal friction material is lost should be encouraged.

- Children should be advised to ride their tricycles only when wearing foot covering. This is especially true for units with spoked wheels because of the dangers of catching a toe between the wheel and fork assembly.

Seat Height

It is recommended that consideration be given to specifying fixed seat height. This serves the purpose of assuring that the seat is always properly aligned with the frame of the unit and it removes the possibility of having insufficient penetration of the seat post in the frame. It also fixes one of the variables in the stability parameter (center-of-gravity height, at least to the extent that this is a function of seat height) and therefore facilitates demonstration of compliance if a stability standard is adopted.

Steering Angle

The possiblity of improving safety of operation by restricting the available steering angle by mechanical stops has been considered. A variation of this approach (which is intended to perform the same function - inhibiting the range of steering) by reducing handlebar width has also been proposed. Although Figure 2 clearly shows steering angle to be a significant variable in rollover stability, it is the combined steering angle - speed function which causes rollover. At very low speed, large angles are permissable and this capability is even desirable for maneuvering in small areas. Thus, restrictions on steering angular freedom to values as low as those indicated by Figure 2 to be necessary for unconditional rollover stability (i.e., in the region of ± 10 degrees for some units) would seem to be inappropriate from the standpoint of overall utility of the toy. Nevertheless an unrestricted range of steering motion is not warranted and based on observations made during this program, this motion might reasonably be limited to certainly less than ± 90 degrees.

Handlebars

One of the problems with curved handlebars which was observed in the test program is that of forcing the rider to lean out of the turn, a condition which tends to promote tipover. In effect, the rotation of the steering mechanism causes the hand grips to intrude into the rider space forcing the rider to lean away. Figure 7 shows this effect. A good design from this standpoint is the straight bar configuration and positive grip handles used on the 14 inch tricycle illustrated in Figure 8.

2.4 Summary of Tricycle Studies

Stability parameters involving design characteristics of three-wheel vehicle toys coupled with rider physical measurements have been derived. Numerical evaluations of these parameters indicate that unstable performance, particularly rollover-while-turning, can occur well within the operational envelopes of many currently available units. In this respect, the tricycle of standard design, especially in the larger sizes, appears to be most culpable. The analytical and experimental results of the tricycle study may be summarized as:

1. The tricycles of traditional design have values for the rollover stability parameter which fall within a very narrow range and which are essentially independent of manufacturer.

2. At comfortable speed (equivalent to pedal crank rotational rates of 60 rpm) and steering angles (producing equivalent radii of turns in the neighborhood of six feet), all test units are stable.

3. All units of traditional design are capable of being rolled over at realizable speeds and steering angles.

4. The rollover stability parameter is only weakly sensitive to rider weight for practical ranges of the weight of

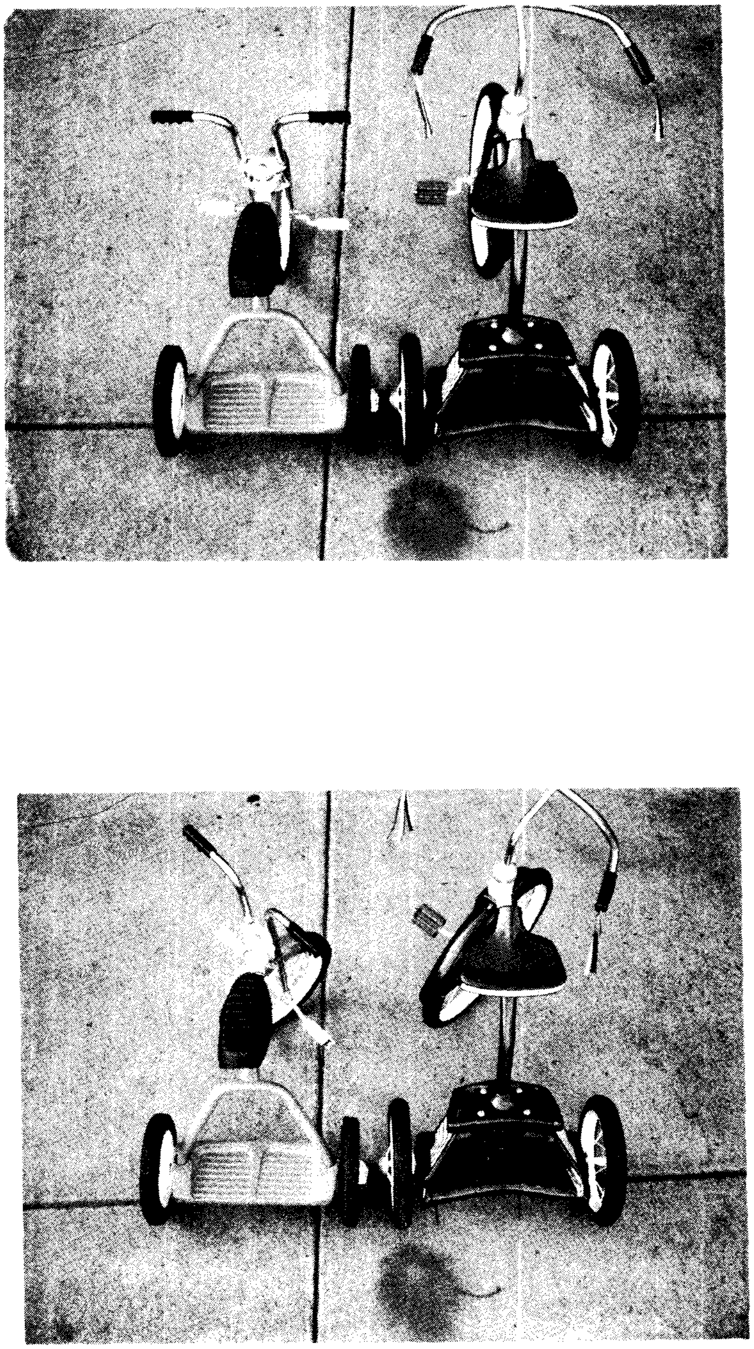


Figure 7 HANDLEBAR DESIGNS – STEERING MOTION

Figure 7 (Cont.) HANDLEBAR DESIGN – LARGE ANGLE STEERING

Figure 8 EXAMPLE OF STRAIGHT HANDLEBAR DESIGN

users.

5. In the rider-only mode of operation, all tricycle models with 40 lb. riders have adequate pitch stability on grades up to 15 degrees if the rider remains seated.

6. Unlike the condition for rollover (which is virtually independent of rider weight), the rearward pitchover stability margin is reduced as rider weight increases. Even so, except for the case of a large child on a small tricycle, the grade producing rear pitchover remains above 10 degrees.

7. The addition of a passenger riding on the rear step reduces rearward pitchover stability margin - especially with the smaller tricycles and lower weight riders (drivers). Limiting grades as low as 7.5 degrees have been calculated for some configurations (10 inch tricycle, 30 lb. rider, 40 lb. passenger in upright position).

3.0 MINIBIKES

The objective of the minibike study was to obtain preliminary information on minibike operational safety - specifically, braking, accelerating and cornering stability on smooth level ground. Attention was also given to the structural integrity, placement of controls, rider position effects, etc.

The approach used was a combined experimental and analytical effort. Detailed measurements of the physical characteristics of seven test minibikes were made. These data were used to estimate the variability in minibike design, to determine the configuration of each minibike which would subsequently be related to the full scale test results, and to provide a basis for computer simulation studies. Full scale experimental tests were then performed. Each minibike was thoroughly tested in several braking, acceleration and cornering maneuvers by an experienced minibike rider. A previously developed digital computer simulation of two-wheel vehicles was used to study the effects of certain design parameters (wheelbase, caster angle, fork offset, etc.) on minibike stability.

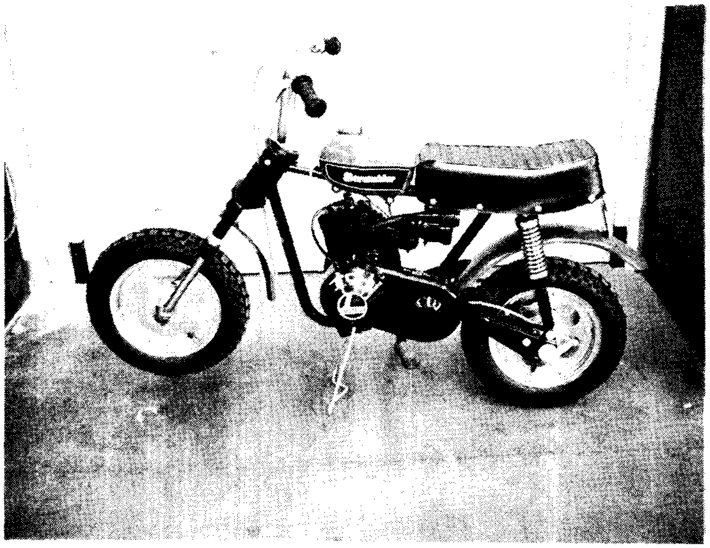
The following sections cover the methods, results and conclusions of these experimental and analytical efforts.

3.1 Measurements of the Physical Characteristics of Minibikes

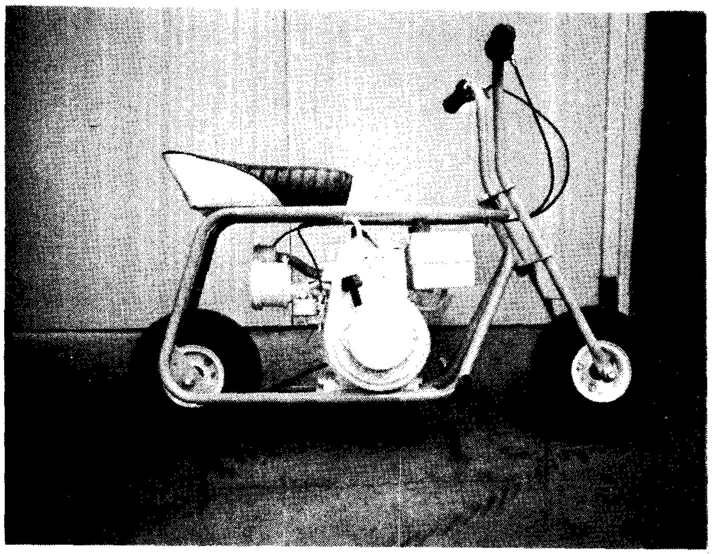
Six minibikes were purchased for use as test vehicles for this program. (Figure 9) A seventh vehicle, owned by Calspan, was also used. The test vehicles, selected from a survey of more than 75 minibikes and 25 manufacturers, represent a broad range of minibike designs. Such characteristics as weight, wheelbase, tire diameter, seat height, and suspension type were considered in selecting the vehicles. Two vehicles were representative of the average minibike size (wheelbase, tire diameter) and the other four were extremes in size and weight. Four front/rear suspension types were represented: rigid front and rigid rear, single external spring front and rigid rear, telescopic front fork and rigid rear, and telescopic front fork and swing arm rear.

Experimental measurements were made to determine the physical characteristics of each minibike. These data included weights, dimensions, and mass moments and products of inertia of the major minibike components (frame, front fork, and wheels).

Weight measurements were obtained with the use of a platform scale having a resolution of ± 0.1 lb. Linear dimensions were measured with scales having a resolution of ± 0.05 inch. Angular measurements were obtained with a vernier inclinometer having ± 1/2 degree resolution. In some cases, specific dimensions were obtained by calculation using other measured parameters. The longitudinal position of the center of gravity of the total vehicle was calculated from measurements of the front-rear wheel weight distribution and the wheelbase dimensions, while the



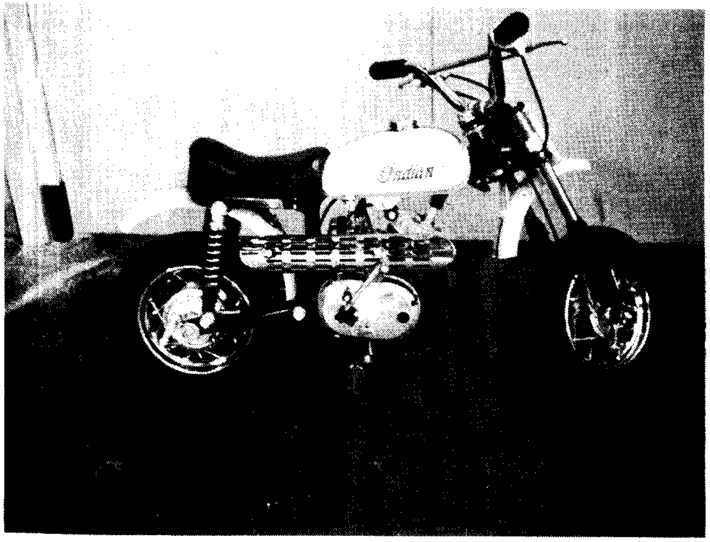
37 INCH WHEELBASE
10 INCH WHEELS
(SCRAMBLER)



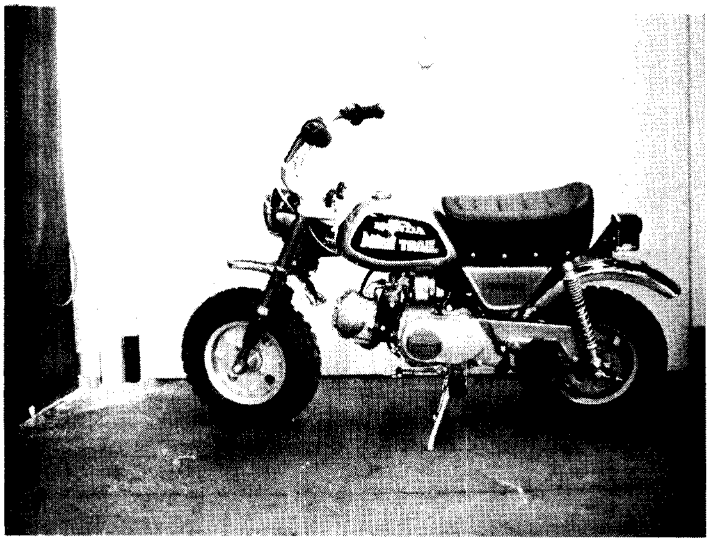
32 INCH WHEELBASE
4 INCH WHEELS
(HORNY TOAD)

36 INCH WHEELBASE
6 INCH WHEELS
(TRAIL FLITE)

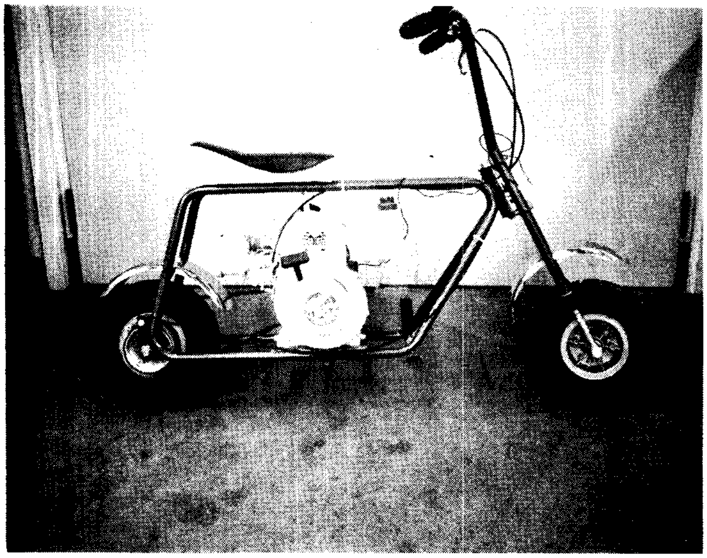
Figure 9a TEST UNITS (MINIBIKES)



30 INCH WHEELBASE
8 INCH WHEELS
(MMSA)



35 INCH WHEELBASE
8 INCH WHEELS
(MINI TRAIL)



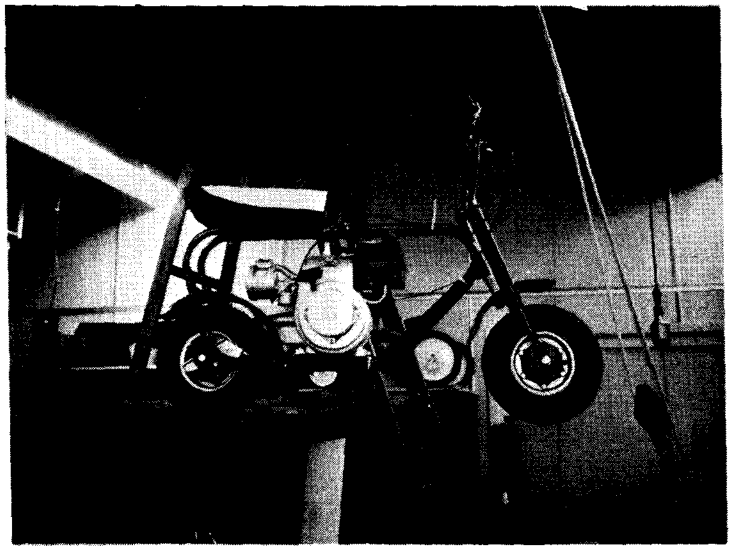
40 INCH WHEELBASE
5 INCH WHEELS
(CHARGER)

Figure 9b TEST UNITS (MINIBIKES)

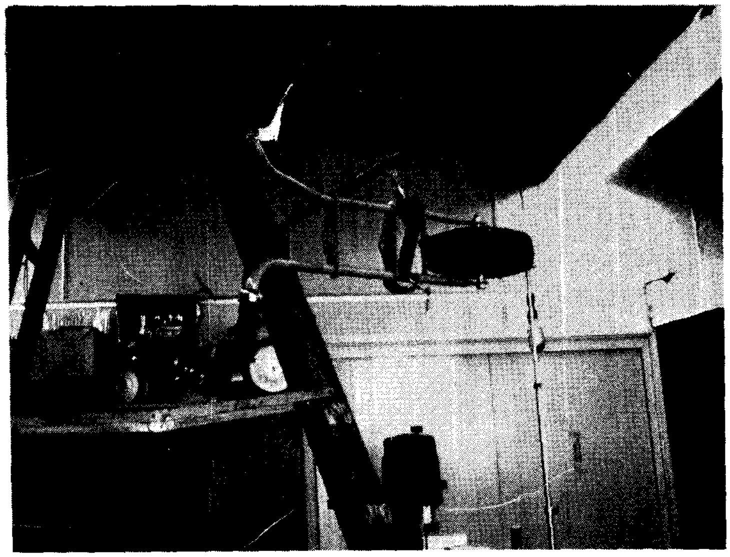
vertical c.g. position was located by finding the intersection of the vertical axis through the c.g. and a vertical line projected from the point of suspension of the inclined frame. Each minibike was suspended from several individual points such that a measurement accuracy of ± 1/8 inch was obtained. Measurement of the c.g. position of the front fork assemblies was determind by suspending each assembly in a horizontal plane at its balance point.

The moments and products of inertia of the total vehicle, the front fork assembly, and the tire/rim assembly were experimentally determined using a torsional pendulum. Each test mass was attached to a long slender rod of known torsional stiffness. The system was set into angular motion and the period of oscillation was measured. A single oscillatory degree of freedom was maintained by placing a bearing just above the test element to prevent radial movement of the torsion rod. The majority of test components were simply attached to the rod and calculation of the moment of inertia was straight forward. In cases where fixtures with significant inertia had to be fabricated to secure the components, appropriate corrections were applied to the experimental data. Figure 10 contains photographs of typical tests.

Tables 6 show the physical characteristics of the seven minibikes. The radial stiffness of the tires was not measured but was assumed to be 200lb/in. Also shown in each page of the table are characteristics of a typical rider. All data are shown



Z-Z AXIS MOMENT OF INERTIA OF COMPLETE UNIT



Y-Y AXIS MOMENT OF INERTIA OF FRONT FORK ASSEMBLY

Figure 10 MINIBIKE MOMENT-OF-INERTIA MEASUREMENTS

PHYSICAL CHARACTERISTICS OF THE HORNY TOA)

WHEELBASE (IN)	32.00
TOTAL WEIGHT OF BICYCLE (LB)	65.30
LOCATION OF TOTAL BICYCLE C.G. FORWARD OF REAR WHEEL CENTER (IN)	14.10
LOCATION OF TOTAL BICYCLE C.G. ABOVE GROUND (IN)	10.30
ROLL MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	8.04
PITCH MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	22.30
YAW MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	16.80
ROLL-YAW PRODUCT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	1.94

WEIGHT OF RIDER (LB)	102.00
LOCATION OF RIDER C.G. FORWARD OF REAR WHEEL CENTER (IN)	9.50
HEIGHT OF RIDER C.G. ABOVE GROUND (IN)	29.60
HEIGHT OF SADDLE ABOVE GROUND (IN)	21.60
ROLL MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	27.80
PITCH MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	39.90
YAW MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	18.40
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 HANOLE BARS),(LB)	11.90
PERPENDICULAR DISTANCE FROM C.G. OF FRONT FORK ASSEMBLY TO STEER AXIS (IN)	2.50
DISTANCE PARALLEL TO STEER AXIS FROM C.G. OF FRONT FORK ASSEMBLY TO FRONT WHEEL CENTER (IN)	8.88
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)	3.80
PITCH MOMENT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT AN AXIS THROUGH THE C.C. OF THE ASSEMBLY (LB-IN-SEC SQ)	3.29
YAW MOMENT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT THE STEER AXIS (LB-IN-SEC SQ)	0.69
ROLL-YAW PRODUCT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT AN AXIS THROUGH THE C.G. OF THE ASSEMBLY (LB-IN-SEC SQ)	0.12

CASTER ANGLE OF THE STEER AXIS (DEG)	27.40
FORK OFFSET (IN)	1.50
UNDEFLECTED WHEEL ROLLING RADIUS (IN)	5.00
TIRE SECTION WIDTH (IN)	3.75
RADIAL STIFFNESS OF TIRE (LB/IN)	200.00
SPIN MOMENT OF INERTIA OF THE FRONT WHEEL (LB-IN-SEC SQ)	0.14
SPIN MOMENT OF INERTIA OF THE REAR WHEEL (LB-IN-SEC SQ)	0.17

Table 6: MINIBIKE PHYSICAL CHARACTERISTICS

PHYSICAL CHARACTERISTICS OF THE CHARGER

WHEELBASE (IN)	40.10
TOTAL WEIGHT OF BICYCLE (LB)	72.30
LOCATION OF TOTAL BICYCLE C.G. FORWARD OF REAR WHEEL CENTER (IN)	18.00
LOCATION OF TOTAL BICYCLE C.G. ABOVE GROUND (IN)	11.50
ROLL MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	11.00
PITCH MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	40.30
YAW MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	32.30
ROLL-YAW PRODUCT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	3.14

WEIGHT OF RIDER (LB)	102.00
LOCATION OF RIDER C.G. FORWARD OF REAR WHEEL CENTER (IN)	13.50
HEIGHT OF RIDER C.G. ABOVE GROUND (IN)	31.30
HEIGHT OF SADDLE ABOVE GROUND (IN)	23.30
ROLL MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	27.80
PITCH MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	39.90
YAW MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	18.40
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)	17.90
PERPENDICULAR DISTANCE FROM C.G. OF FRONT FORK ASSEMBLY TO STEER AXIS (IN)	1.25
DISTANCE PARALLEL TO STEER AXIS FROM C.G. OF FRONT FORK ASSEMBLY TO FRONT WHEEL CENTER (IN)	10.80
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)	6.67
PITCH MOMENT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT AN AXIS THROUGH THE C.G. OF THE ASSEMBLY (LB-IN-SEC SQ)	6.25
YAW MOMENT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT THE STEER AXIS (LB-IN-SEC SQ)	0.59
ROLL-YAW PRODUCT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT AN AXIS THROUGH THE C.G. OF THE ASSEMBLY (LB-IN-SEC SQ)	0.22

CASTER ANGLE OF THE STEER AXIS (DEG)	27.20
FORK OFFSET (IN)	1.25
UNDEFLECTED WHEEL ROLLING RADIUS (IN)	5.60
TIRE SECTION WIDTH (IN)	3.50
RADIAL STIFFNESS OF TIRE (LB/IN)	200.00
SPIN MOMENT OF INERTIA OF THE FRONT WHEEL (LB-IN-SEC SQ)	0.23
SPIN MOMENT OF INERTIA OF THE REAR WHEEL (LB-IN-SEC SQ)	0.28

Table 6 (Cont.): MINIBIKE PHYSICAL CHARACTERISTICS

PHYSICAL CHARACTERISTICS OF THE TRAIL ELITE

WHEELBASE (IN)	36.00
TOTAL WEIGHT OF BICYCLE (LB)	79.20
LOCATION OF TOTAL BICYCLE C.G. FORWARD OF REAR WHEEL CENTER (IN)	15.30
LOCATION OF TOTAL BICYCLE C.G. ABOVE GROUND (IN)	12.00
ROLL MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	10.70
PITCH MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	40.60
YAW MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	33.10
ROLL-YAW PRODUCT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	-1.70

WEIGHT OF RIDER (LB)	102.00
LOCATION OF RIDER C.G. FORWARD OF REAR WHEEL CENTER (IN)	10.00
HEIGHT OF RIDER C.G. ABOVE GROUND (IN)	32.90
HEIGHT OF SADDLE ABOVE GROUND (IN)	24.90
ROLL MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	27.80
PITCH MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	39.90
YAW MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	18.40
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)	16.80
PERPENDICULAR DISTANCE FROM C.G. OF FRONT FORK ASSEMBLY TO STEER AXIS (IN)	1.50
DISTANCE PARALLEL TO STEER AXIS FROM C.G. OF FRONT FORK ASSEMBLY TO FRONT WHEEL CENTER (IN)	7.00
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)	4.90
PITCH MOMENT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT AN AXIS THROUGH THE C.G. OF THE ASSEMBLY (LB-IN-SEC SQ)	4.73
YAW MOMENT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT THE STEER AXIS (LB-IN-SEC SQ)	0.77
ROLL-YAW PRODUCT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT AN AXIS THROUGH THE C.G. OF THE ASSEMBLY (LB-IN-SEC SQ)	0.02

CASTER ANGLE OF THE STEER AXIS (DEG)	17.80
FORK OFFSET (IN)	1.50
UNDEFLECTED WHEEL ROLLING RADIUS (IN)	6.13
TIRE SECTION WIDTH (IN)	3.63
RADIAL STIFFNESS OF TIRE (LB/IN)	200.00
SPIN MOMENT OF INERTIA OF THE FRONT WHEEL (LB-IN-SEC SQ)	0.35
SPIN MOMENT OF INERTIA OF THE REAR WHEEL (LB-IN-SEC SQ)	0.42

Table 6 (Cont.): MINIBIKE PHYSICAL CHARACTERISTICS

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                                        PHYSICAL CHARACTERISTICS OF THE SPOILER

WHEELBASE (IN)                                          36.00    WEIGHT OF RIDER (LB)                                 102.00

TOTAL WEIGHT OF BICYCLE (LB)                            95.90    LOCATION OF RIDER C.G. FORWARD                        11.00
                                                                 OF REAR WHEEL CENTER (IN)
LOCATION OF TOTAL BICYCLE C.G.                          15.20
FORWARD OF REAR WHEEL CENTER (IN)                                HEIGHT OF RIDER C.G. ABOVE GROUND (IN)                32.80

LOCATION OF TOTAL BICYCLE C.G.                          13.10    HEIGHT OF SADDLE ABOVE GROUND (IN)                    24.80
ABOVE GROUND (IN)
                                                                 ROLL MOMENT OF INERTIA OF RIDER ABOUT                 27.30
ROLL MOMENT OF INERTIA OF THE TOTAL BICYCLE             13.10    AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)
ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)
                                                                 PITCH MOMENT OF INERTIA OF RIDER ABOUT                39.90
PITCH MOMENT OF INERTIA OF THE TOTAL BICYCLE            40.20    AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)
ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)
                                                                 YAW MOMENT OF INERTIA OF RIDER ABOUT                  18.40
YAW MOMENT OF INERTIA OF THE TOTAL BICYCLE              30.70    AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)
ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)
                                                                 ROLL-YAW PRODUCT OF INERTIA OF RIDER ABOUT             0.0
ROLL-YAW PRODUCT OF INERTIA OF THE TOTAL BICYCLE        -3.16    AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)
ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)



WEIGHT OF FRONT FORK ASSEMBLY                           17.60    CASTER ANGLE OF THE STEER AXIS (DEG)                  24.20
(FORK,WHEEL,AND HANDLE BARS),(LB)
                                                                 FORK OFFSET (IN)                                       1.38
PERPENDICULAR DISTANCE FROM C.G. OF FRONT                1.63
FORK ASSEMBLY TO STEER AXIS (IN)                                 UNDEFLECTED WHEEL ROLLING RADIUS (IN)                  7.63

DISTANCE PARALLEL TO STEER AXIS FROM C.G. OF             9.00    TIRE SECTION WIDTH (IN)                                2.50
FRONT FORK ASSEMBLY TO FRONT WHEEL CENTER (IN)
                                                                 RADIAL STIFFNESS OF TIRE (LB/IN)                     200.00
ROLL MOMENT OF INERTIA OF FRONT FORK
ASSEMBLY ABOUT AN AXIS PERPENDICULAR TO THE              4.92    SPIN MOMENT OF INERTIA OF THE FRONT                    0.50
STEER AXIS THROUGH C.G. OF ASSEMBLY (LB-IN-SEC SQ)               WHEEL (LB-IN-SEC SQ)

PITCH MOMENT OF INERTIA OF FRONT FORK                            SPIN MOMENT OF INERTIA OF THE REAR                     0.60
ASSEMBLY ABOUT AN AXIS THROUGH THE C.G.                  4.87    WHEEL (LB-IN-SEC SQ)
OF THE ASSEMBLY (LB-IN-SEC SQ)

YAW MOMENT OF INERTIA OF FRONT FORK                      0.83
ASSEMBLY ABOUT THE STEER AXIS (LB-IN-SEC SQ)

ROLL-YAW PRODUCT OF INERTIA OF FRONT
FORK ASSEMBLY ABOUT AN AXIS THROUGH                      0.37
THE C.G. OF THE ASSEMBLY (LB-IN-SEC SQ)
```

Table 6 (Cont.): MINIBIKE PHYSICAL CHARACTERISTICS

PHYSICAL CHARACTERISTICS OF THE SCRAMBLER

WHEELBASE (IN)	37.00
TOTAL WEIGHT OF BICYCLE (LB)	100.00
LOCATION OF TOTAL BICYCLE C.G. FORWARD OF REAR WHEEL CENTER (IN)	16.00
LOCATION OF TOTAL BICYCLE C.G. ABOVE GROUND (IN)	13.50
ROLL MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	14.60
PITCH MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	54.40
YAW MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	43.50
ROLL-YAW PRODUCT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	-1.80

WEIGHT OF FRONT FORK ASSEMBLY (FORK,WHEEL,AND HANDLE BARS),(LB)	22.30
PERPENDICULAR DISTANCE FROM C.G. OF FRONT FORK ASSEMBLY TO STEER AXIS (IN)	1.25
DISTANCE PARALLEL TO STEER AXIS FROM C.G. OF FRONT FORK ASSEMBLY TO FRONT WHEEL CENTER (IN)	8.56
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)	6.47
PITCH MOMENT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT AN AXIS THROUGH THE C.G. OF THE ASSEMBLY (LB-IN-SEC SQ)	6.41
YAW MOMENT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT THE STEER AXIS (LB-IN-SEC SQ)	1.09
ROLL-YAW PRODUCT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT AN AXIS THROUGH THE C.G. OF THE ASSEMBLY (LB-IN-SEC SQ)	-0.44

WEIGHT OF RIDER (LB)	102.00
LOCATION OF RIDER C.G. FORWARD OF REAR WHEEL CENTER (IN)	6.00
HEIGHT OF RIDER C.G. ABOVE GROUND (IN)	34.00
HEIGHT OF SADDLE ABOVE GROUND (IN)	26.00
ROLL MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	27.80
PITCH MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	39.90
YAW MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	18.40
ROLL-YAW PRODUCT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	0.0

CASTER ANGLE OF THE STEER AXIS (DEG)	31.60
FORK OFFSET (IN)	1.25
UNDEFLECTED WHEEL ROLLING RADIUS (IN)	8.25
TIRE SECTION WIDTH (IN)	3.13
RADIAL STIFFNESS OF TIRE (LB/IN)	200.00
SPIN MOMENT OF INERTIA OF THE FRONT WHEEL (LB-IN-SEC SQ)	0.77
SPIN MOMENT OF INERTIA OF THE REAR WHEEL (LB-IN-SEC SQ)	0.92

Table 6 (Cont.): MINIBIKE PHYSICAL CHARACTERISTICS

PHYSICAL CHARACTERISTICS OF THE MMSA

WHEELBASE (IN)	30.00
TOTAL WEIGHT OF BICYCLE (LB)	57.30
LOCATION OF TOTAL BICYCLE C.G. FORWARD OF REAR WHEEL CENTER (IN)	13.80
LOCATION OF TOTAL BICYCLE C.G. ABOVE GROUND (IN)	10.30
ROLL MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	5.25
PITCH MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	16.90
YAW MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	13.70
ROLL-YAW PRODUCT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	-1.16

WEIGHT OF RIDER (LB)	102.00
LOCATION OF RIDER C.G. FORWARD OF REAR WHEEL CENTER (IN)	9.50
HEIGHT OF RIDER C.G. ABOVE GROUND (IN)	25.90
HEIGHT OF SADDLE ABOVE GROUND (IN)	17.90
ROLL MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	27.80
PITCH MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	39.90
YAW MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	18.40
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)	12.60
PERPENDICULAR DISTANCE FROM C.G. OF FRONT FORK ASSEMBLY TO STEER AXIS (IN)	2.63
DISTANCE PARALLEL TO STEER AXIS FROM C.G. OF FRONT FORK ASSEMBLY TO FRONT WHEEL CENTER (IN)	7.25
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)	2.58
PITCH MOMENT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT AN AXIS THROUGH THE C.G. OF THE ASSEMBLY (LB-IN-SEC SQ)	2.52
YAW MOMENT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT THE STEER AXIS (LB-IN-SEC SQ)	0.58
ROLL-YAW PRODUCT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT AN AXIS THROUGH THE C.G. OF THE ASSEMBLY (LB-IN-SEC SQ)	-0.44

CASTER ANGLE OF THE STEER AXIS (DEG)	27.80
FORK OFFSET (IN)	2.13
UNDEFLECTED WHEEL ROLLING RADIUS (IN)	6.30
TIRE SECTION WIDTH (IN)	2.50
RADIAL STIFFNESS OF TIRE (LB/IN)	200.00
SPIN MOMENT OF INERTIA OF THE FRONT WHEEL (LB-IN-SEC SQ)	0.23
SPIN MOMENT OF INERTIA OF THE REAR WHEEL (LB-IN-SEC SQ)	0.28

Table 6 (Cont.): MINIBIKE PHYSICAL CHARACTERISTICS

PHYSICAL CHARACTERISTICS OF THE MINI-TRAIL

WHEELBASE (IN)	35.20
TOTAL WEIGHT OF BICYCLE (LB)	117.00
LOCATION OF TOTAL BICYCLE C.G. FORWARD OF REAR WHEEL CENTER (IN)	15.50
LOCATION OF TOTAL BICYCLE C.G. ABOVE GROUND (IN)	13.50
ROLL MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	13.70
PITCH MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	49.20
YAW MOMENT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	39.90
ROLL-YAW PRODUCT OF INERTIA OF THE TOTAL BICYCLE ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)	-1.58

WEIGHT OF RIDER (LB)	102.00
LOCATION OF RIDER C.G. FORWARD OF REAR WHEEL CENTER (IN)	10.50
HEIGHT OF RIDER C.G. ABOVE GROUND (IN)	32.30
HEIGHT OF SADDLE ABOVE GROUND (IN)	24.30
ROLL MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	27.80
PITCH MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	39.90
YAW MOMENT OF INERTIA OF RIDER ABOUT AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)	18.40
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)	25.40
PERPENDICULAR DISTANCE FROM C.G. OF FRONT FORK ASSEMBLY TO STEER AXIS (IN)	1.50
DISTANCE PARALLEL TO STEER AXIS FROM C.G. OF FRONT FORK ASSEMBLY TO FRONT WHEEL CENTER (IN)	9.25
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)	6.87
PITCH MOMENT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT AN AXIS THROUGH THE C.G. OF THE ASSEMBLY (LB-IN-SEC SQ)	6.61
YAW MOMENT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT THE STEER AXIS (LB-IN-SEC SQ)	1.14
ROLL-YAW PRODUCT OF INERTIA OF FRONT FORK ASSEMBLY ABOUT AN AXIS THROUGH THE C.G. OF THE ASSEMBLY (LB-IN-SEC SQ)	-0.48

CASTER ANGLE OF THE STEER AXIS (DEG)	25.00
FORK OFFSET (IN)	1.50
UNDEFLECTED WHEEL ROLLING RADIUS (IN)	7.50
TIRE SECTION WIDTH (IN)	3.69
RADIAL STIFFNESS OF TIRE (LB/IN)	200.00
SPIN MOMENT OF INERTIA OF THE FRONT WHEEL (LB-IN-SEC SQ)	0.55
SPIN MOMENT OF INERTIA OF THE REAR WHEEL (LB-IN-SEC SQ)	0.67

Table 6 (Cont.): **MINIBIKE PHYSICAL CHARACTERISTICS**

in the input format required for the computer simulation program. (Section 3.3)

3.2 Full Scale Minibike Performance Tests

The full scale test program was concentrated on obtaining baseline performance data on minibikes which is an essential early step in the formulation of standards. A direct benefit of this work was the identification of several performance factors which merit consideration as subjects for safety standards. Emphasis was placed on the braking, accelerating, and cornering stability characteristics on smooth level ground. In addition, a special test was devised to simulate off-road bump jumping. The full scale tests were performed by an experienced teen-age rider on the skid pad of the Calspan Vehicle Experimental Test Facility. In all tests, objective measurements of performance were supplemented with subjective evaluations by the rider (Appendix D). 16 mm motion pictures and still photographs were taken of all phases of the test program. Over 300 test runs were performed to obtain data on the operating envelopes of each vehicle.

The following is a description of the braking, accelerating, steady cornering, and maneuvering tests which were employed. Table 7 contains the resultant performance figures for each minibike (except the MMSA which was not included in the normal full scale tests because of its extremely small size).

Table 7
SUMMARY OF FULL SCALE TEST RESULTS

	TOAD	CHARGER	TRAIL FLITE	SPOILER	SCRAMBLER	MINI TRAIL	MMSA**
STOPPING DISTANCE FROM 15 MPH (ft)	13.7	14.0	14.3	11.7	12.7	8.3*	--
EQUIVALENT DECELERATION (g's)	0.55	0.54	0.53	0.64	0.59	0.91*	--
ELAPSED TIME TO TRAVEL 75 ft. FROM STANDING START (sec.)	5.6	5.8	4.6	4.1	3.7	4.2	--
EQUIVALENT AVERAGE ACCELERATION (g's)	0.15	0.14	0.22	0.28	0.33	0.27	--
MAXIMUM SPEED WITH GOVERNOR (MPH)	21.2	23.3	18.8	21.1	32.3	--	--
MAXIMUM SPEED WIDE OPEN THROTTLE (MPH)	26.0	31.3	28.2	24.5	33.5	27.9	12.0
MAXIMUM STEADY LATERAL ACCELERATION (g's)	0.61	0.63	0.65	0.74	0.71	0.73	--
AVERAGE TIME THROUGH SLALOM COURSE (sec.)	20.4	20.0	19.1	18.2	18.2	18.7	--
AVERAGE NUMBER OF STEERING CORRECTIONS THROUGH SLALOM COURSE	24	24	22	16	18	7	--

* USING FRONT AND REAR BRAKES SIMULTANEOUSLY [REAR BRAKE ONLY: 16.3 feet (0.46 g), FRONT BRAKE ONLY: 12.3 feet (0.61 g)].

**SEVERAL TESTS WERE NOT PERFORMED WITH THE MMSA MINIBIKE BECAUSE OF ITS LIMITED SPEED CAPABILITY.

Table 8 contains descriptions of the types of brake mechanisims, control levers, engine sizes, tires, etc. used on each minibike.

Braking Tests

Stopping distances from a speed of 15 mph were measured using a pace car with a calibrated speedometor for accurate speed control. All minibikes tested had rear wheel brakes only except the Minitrail which had both front and rear wheel brakes. All rear wheel brakes had left hand lever controls except the Minitrail which had a right foot control for the rear wheel brake and a right hand lever control for the front wheel brake. On all minibikes the brakes were sufficiently effective to lock the rear wheel. Therefore, the braking capability as measured was primarily a function of tire/pavement friction and the dimensions of the minibike (total c.g. height and wheelbase) and was not limited by the braking mechanism. Generally, it was not possible to lock the front wheel of the Minitrail because of excessive hand grip force requirements. This is desirable since locking of the front wheel results in loss of steering control which would be hazardous when braking at speed or in a turn. Three braking runs were made with each minibike and the average stopping distances from 15 mph and equivalent decelerations were computed as shown in Table 7. Figure 11 is a photograph of a typical test.

Table 8

MINIBIKE COMPONENT SPECIFICATIONS

	TOAD	CHARGER	TRAIL FILTE	SPOILER	SCRAMBLER	MINI TRAIL	MMSA
REAR BRAKE CONTROL	LEFT HAND	LEFT HAND	LEFT HAND	LEFT HAND	LEFT HAND	RIGHT HAND	RIGHT HAND
FRONT BRAKE CONTROL	---	---	---	---	---	RIGHT FOOT	RIGHT FOOT
TYPE OF BRAKE MECHANISM*	B1	B2	B2	B3	B4	B4	B4
ENGINE HORSEPOWER	3.0	3.0	3.0	4.0	3.5	1.9	1.3
CLUTCH	CENTRIF	CENTRIF	CENTRIF	CENTRIF	CENTRIF	CENTRIF	CENTRIF
TRANSMISSION	NONE	NONE	NONE	NONE	TORQUE CONVERTER	MANUAL 3 SPEED	AUTO SINGLE SPEED
THROTTLE CONTROL		RIGHT HAND AND COUNTERCLOCKWISE TO OPEN ON ALL MINIBIKES					
ON-OFF SWITCH	NONE	NONE	MOMENTARY RIGHT HAND	NONE	MOMENTARY LEFT HAND	POSITIVE RIGHT HAND	MOMENTARY LEFT HAND
TIRE SIZE	4.10/3.50-4	4.10/3.50-5	4.10/3.50-6	2.50-10	3.00-10	3.50-8	2.50-8
TIRE CROSS SECTION	SQUARE	SQUARE	ROUND	ROUND	ROUND	ROUND	ROUND
TIRE TREAD TYPE	DIRT	DIRT	DIRT	KNOBBY	KNOBBY	KNOBBY	KNOBBY
OUTSIDE TIRE DIAMETER (in.)	10.0	11.2	12.3	15.3	16.5	15.0	12.6
FRONT SUSPENSION	RIGID	TELESCOPIC FORKS	SINGLE EXT. SPRING	TELESCOPIC FORKS	TELESCOPIC FORKS	TELESCOPIC FORKS	TELESCOPIC FORKS
HYDRAULIC DAMPER	NO	NO	NO	NO	NO	NO	NO
REAR SUSPENSION	RIGID	RIGID	RIGID	SWING ARM	SWING ARM	SWING ARM	SWING ARM
HYDRAULIC DAMPER	NO	NO	NO	NO	NO	NO	NO
CASTER ANGLE (deg.)	27.4	27.2	17.8	24.2	31.6	25.0	27.8
STEERING TRAIL (in.)	0.9	1.5	0.4	1.9	3.6	1.8	0.9

*B1 - CONTRACTING BAND TYPE BRAKE MOUNTED ON CLUTCH
B2 - CONTRACTING BAND TYPE BRAKE MOUNTED ON WHEEL
B3 - DISK BRAKE WITH CAM OPERATED DUAL PAD FLOATING CALIPER
B4 - INTERNAL EXPANDING TYPE DRUM BRAKE

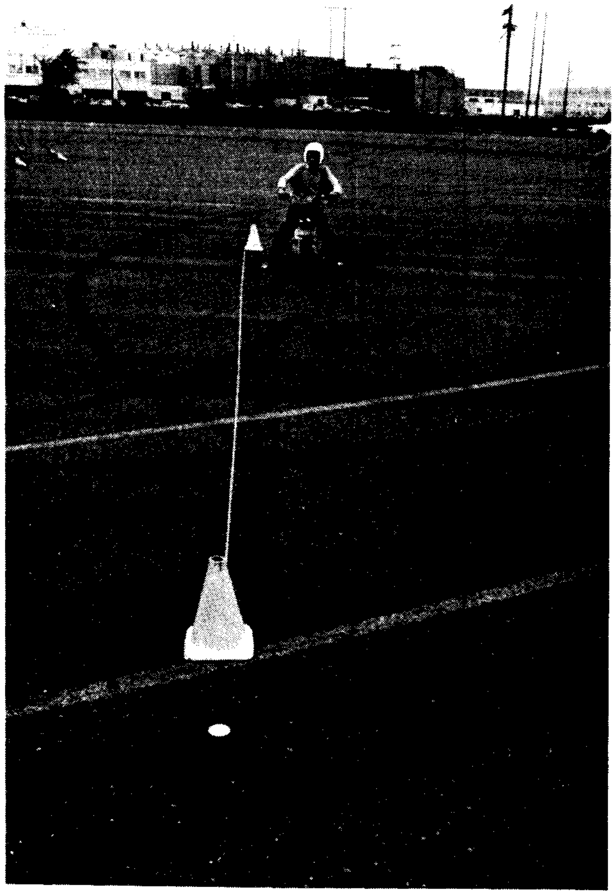


Figure 11 MINIBIKE BRAKING TEST

Acceleration Tests

The time taken to travel 75 feet from a standing start was measured. Five runs were made with each minibike and the average elapsed times and equivalent average acceleration over the 75 foot distance were computed (Table 7). Figures 12 and 13 show examples of these tests. Figure 13 is especially interesting because it demonstrates a tendency of some units to produce inadvertent "wheelies" on acceleration. This is discussed further in a supplementary subjective evaluation report.

Maximum Speed Tests

The elapsed time to travel a fixed distance was measured to determine maximum speed of the minibikes. Each minibike was tested with normal throttle governor operation and with the throttle governor inoperative (i.e., wide open throttle). Since the Minitrail and MMSA had no throttle governors, only one configuration was tested with these units. Elapsed times (running the fixed distance course in both directions to correct for wind effects) were used to compute maximum speeds from the average of three round-trip runs with each minibike in each throttle configuration, Table 7.

Steady Cornering Tests

The elapsed time to travel around a 25 foot radius circle was measured to determine steady-state cornering capability

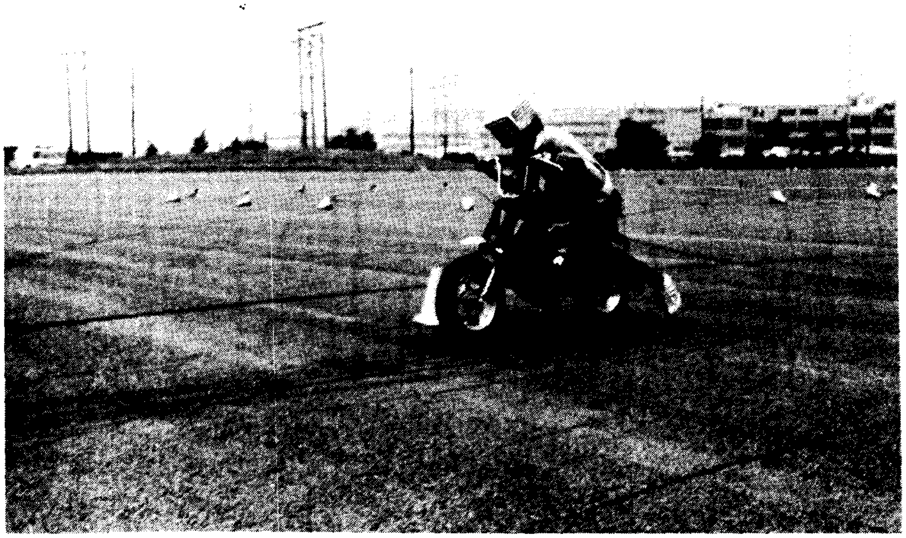


Figure 12 MINIBIKE ACCELERATION TEST

Figure 13 MINIBIKE ACCELERATION "WHEELIE"

in terms of maximum lateral acceleration. Figures 14 and 15 are photographs of typical tests. A circular course was constructed with traffic cones set in a circular pattern. The cones were placed 27 feet from the center of the circle so that the path of the vehicle center of gravity had a radius of approximately 25 feet. The lateral acceleration Ay (in g's) of each minibike was computed from the expression: $Ay=\frac{4\pi^2 R}{g T^2}$, where R is the radius of the circular path (25 feet) and T is the time required to lap the course. The average elapsed time for ten runs was used to compute the maximum lateral acceleration for each minibike, Table 7 .

Handling Tests

Evaluation of handling quality depends on the experimenter's ability to obtain valid objective measurements of system (the rider-vehicle combination) performance. Since the rider is often capable of modifying his own control characteristics to compensate for deficiencies of the machine in the performance of a specific task, the avoidance of ambiguous results can only be achieved with careful consideration of the makeup of the task and the selection of the metrics used for evaluation.

The full scale minibike handling tests were based on the theory that the relative handling capabilities of the six minibikes could best be determined if rider control activity measurements as well as overall performance measurements were

Figure 14 HARD CORNERING IN THE MINIBIKE LATERAL ACCELERATION TEST
[Note foot peg on inside]

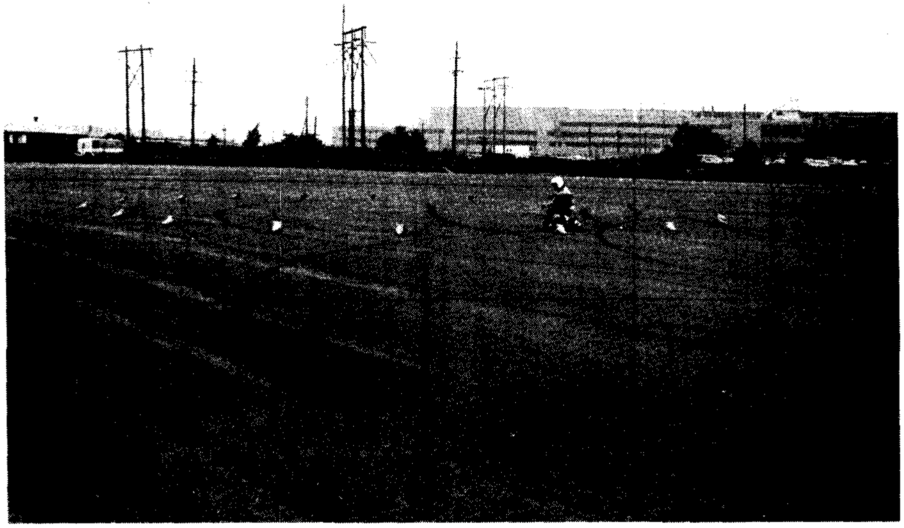


Figure 15 MINIBIKE LATERAL ACCELERATION TEST

taken. The task used in the minibike handling evaluation was a thirteen pylon slalom course, Figure 16. The procedure for running the course (Figures 17 and 18) was as follows. After entering the start/finish gate the pylon to the right was looped first. Continuing through the course, the rider circled the last pylon which was positioned on the centerline of the course and returned through the course in the opposite direction, finally exiting through the start/finish gate. The test rider was instructed to run the course at constant throttle to minimize the effect of power differences between vehicles.

Each minibike was instrumented with a device to count steering reversals. The device was switched on and off when the minibike entered and exited the start/finish gate. Ideally the course could be run with exactly sixteen steering reversals (in fact this was accomplished once with the Mini Trail). The number of steering reversals in excess of sixteen represent steering corrections necessary to compensate for vehicle deficienies and/or correct for rider errors. The elapsed time required to run the course was measured as the criterion of overall performance

The handling tests were run as the last series of the full scale tests to maximize the test rider's experience with all minibikes. Furthermore, the test rider was allowed to practice about one half hour before data runs were made. Approximately ten test runs were made with each minibike. After the series

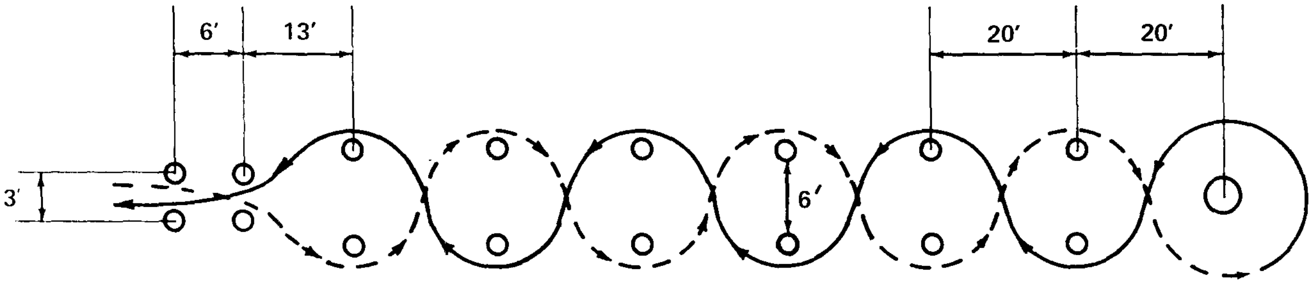


Figure 16 SCHEMATIC DIAGRAM OF MINIBIKE SLALOM COURSE

Figure 17 MINIBIKE HANDLING TEST

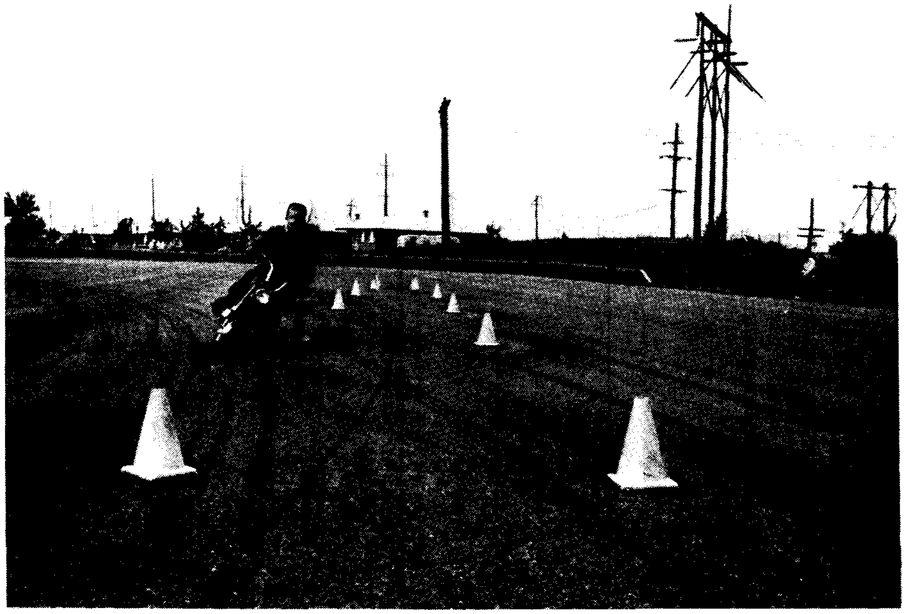


Figure 18 HARD MANEUVERING IN HANDLING TEST

of six minibikes were completed, testing of the first and second of the series was repeated and data were averaged with the initial runs to minimize the effects of training. Table 7 shows the average times and average number of steering corrections (total steering reversals minus sixteen) for each of the six minibikes tested in the slalom course.

The three minibikes with the longest times and most steering corrections were also those with the lowest steady state lateral acceleration capability. These three minibikes also had (on the average) about 60% less steering trail than the three better performing minibikes. Lateral acceleration capability and steering trail are known to be important factors in determining two-wheel vehicle handling. Furthermore, the three slower minibikes had no rear suspensions and the two slowest minibikes had in addition square profile tires with the smallest outside diameter.

On the basis of average elapsed times the worst minibike was about 12% slower than the fastest. One minibike required significantly fewer steering corrections than the others (less than half the next best), although it was not the best in overall performance. It is interesting to note that this minibike became the "favorite" of a group of casual minibike riders asked to give their subjective evaluations of the test fleet. This is consistant with the results of the full scale handling test which showed that this minibike is the easiest to control.

Bump Jumping Tests

The purpose of the bump jumping test was to qualitatively evaluate the tendency of minibikes to pitch the rider off when hitting bumps at low speeds. The bump used in the test was 4.5 inches high at the center and about 5 feet long with a smooth ramp-like profile, Figure 19. Each minibike was ridden over the bump at approximately 7 mph. 16 mm motion pictures were made of all bump jumping runs.

The first run with each minibike was with the rider seated. Minibikes with rear suspensions (with no shock absorbers) tended to catapult the rider over the handle bars. In fact, in the first trial run using the bump, the rider having been thrown over the handle bars, lost control of the vehicle and fell off (unfortunately, motion pictures were not made of this run). This experience proved that even an experienced rider can be thrown (at relatively low speeds, 7 mph) if he is surprised by a sudden bump while in the seated position. Minibikes with no rear suspensions (rigid frames) did not tend to throw the rider nearly as badly as those with rear springs. However, the "shock" of hitting the bump was much more severe.

Successive runs were made with each minibike with the rider standing on the foot pegs. By absorbing the shock with his legs and by jerking the handle bars the rider was able to control the pitching to a greater or lesser degree depending on

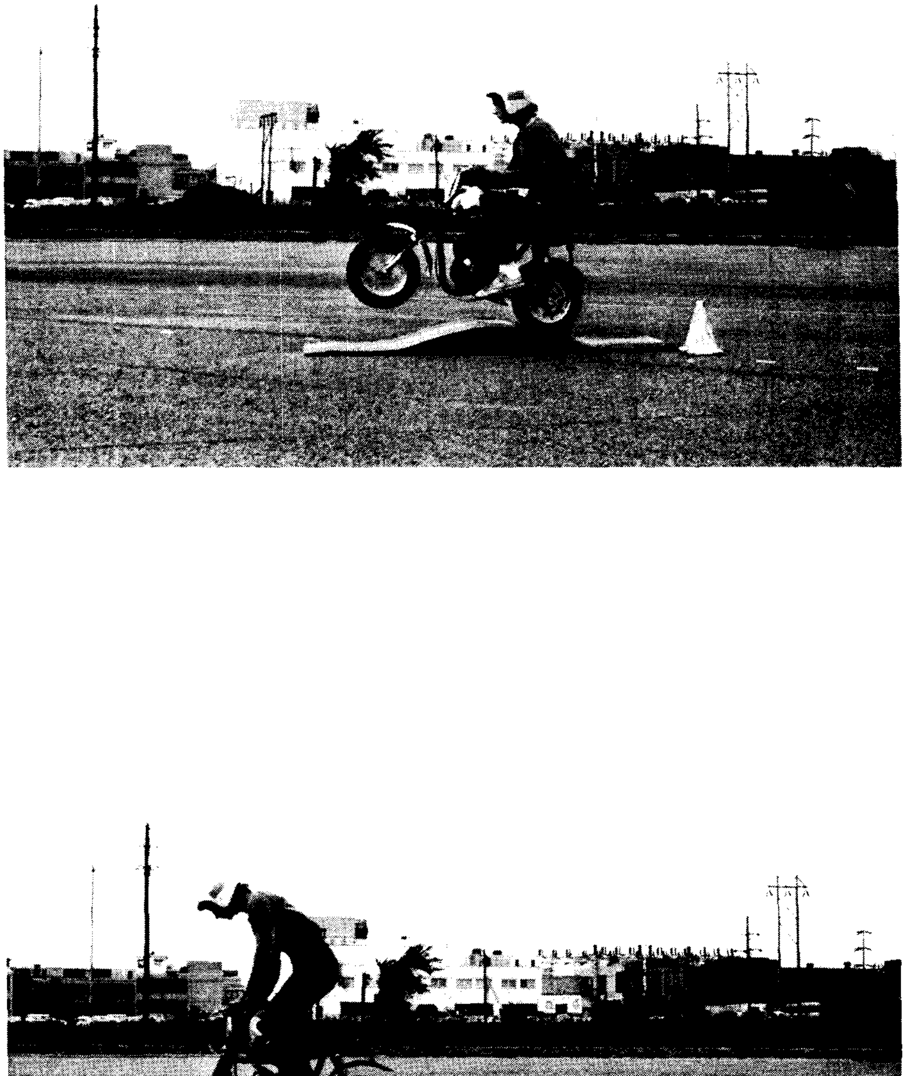


Figure 19 MINIBIKE BUMP-JUMP TEST

the particular minibike. A separate report contains evaluation by the test rider of each minibike in the bump jumping test.

These tests certainly indicated that a possibly hazardous situation can occur with minibikes having undamped rear suspensions. Further testing to determine the improvement which can be gained by using shock absorbers on rear suspensions is recommended.

3.3 Computer Simulation of Minibike

Approximately two years ago, Calspan undertook a brief study of bicycle stability and control under sponsorship of the National Commission on Product Safety. This work is reported in Reference 1 . One of the principal results of this work was the development of a mathematical model of the two-wheeled vehicle, a task which was supported in part by CAL internal research funds.

For the last year CAL has been engaged in a general program on bicycle dynamics. A fundamental objective of this program was the development and validation of a comprehensive digital computer simulation of a bicycle and rider based on the previous mathematical model. The development of this computer program was supported by the measurement of the physical properties of several bicycles and full scale experimental validation tests.

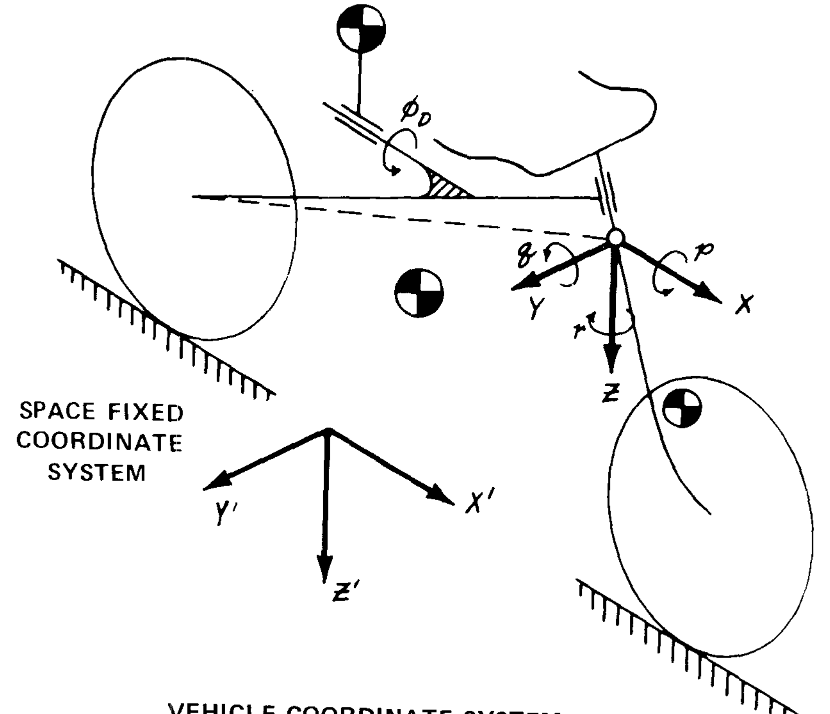
This simulation, which includes a rider control model with steer and rider lean degrees of freedom, is operational and is currently being used for bicycle stability analyses (References 2 and 3).

The basic equations of motion of the mathematical model are in general valid for all single-track two wheel vehicles. Furthermore, the computer program has been written with a generalized subroutine format which allows easy modification and extension for studying a wide range of two-wheel vehicles.

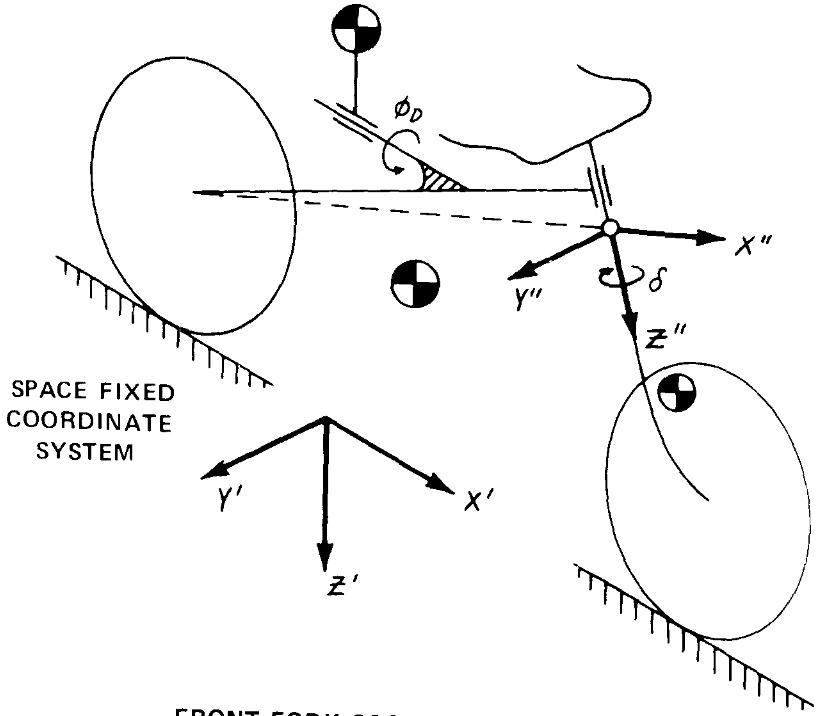
The Calspan two-wheel vehicle simulation provides an efficient means of studying the effects of design parameters and riding conditions on minibike stability and handling. Without building prototype hardware or risking personal safety, simulated tests can be performed on new design concepts over an unlimited speed range and for many road and riding conditions. An additional advantage is that the simulation results are of the same type as from actual experimental tests: time histories of the motions of the vehicle. Moreover, instrumentation is not required and the choice of motion variable to be observed is unlimited.

Current Status of the Computer Simulation

The vehicle-rider model on which the simulation is based is a system of three rigid masses with eight degrees of freedom - six rigid body degrees of freedom, a steer degree of freedom of the front wheel, and a rider-lean degree of freedom (Figure 20). Included in the analysis are tire radial stiffness,



VEHICLE COORDINATE SYSTEM



FRONT FORK COORDINATE SYSTEM

Figure 20 TWO-WHEEL VEHICLE MODEL

tire side forces due to slip angle and inclination (camber) angle, the gyroscopic effects of the rotating wheels, steering moments due to tire side and vertical forces, as well as all inertial coupling terms between the rider, the front wheel and steering fork, and the rear wheel and frame.

Figure 21 shows the physical parameters of the vehicle which are included in the mathematical analysis. The symbols M_D, M_R, M_F, are the masses of the rider, the rear wheel and frame, and the front wheel and steering fork assembly, respectively. The mass distribution of the vehicle is assumed to be symmetrical with respect to the vertical-longitudinal plane through the vehicle's geometrical center. Thus the X-Y and Y-Z products of inertia are zero; otherwise the Y-Z products of inertia and all moments of inertia of each rigid mass are included. θ_F is the caster angle of the steer axis and δ is the steer angle of the front wheel about the inclined steer axis. Reference 2 contains a complete description of the mathematical analysis. The final matrix equation of motion of the complete eight degrees of freedom system is shown in Figure 22.

The rider control model consists of two related modes of operation - a roll stabilization function and a guidance function. Both of these control functions have been developed for rider steer control. The roll stabilization function has been incorporated in the bicycle simulation and is operational. Current work is aimed at implementing the guidance function for

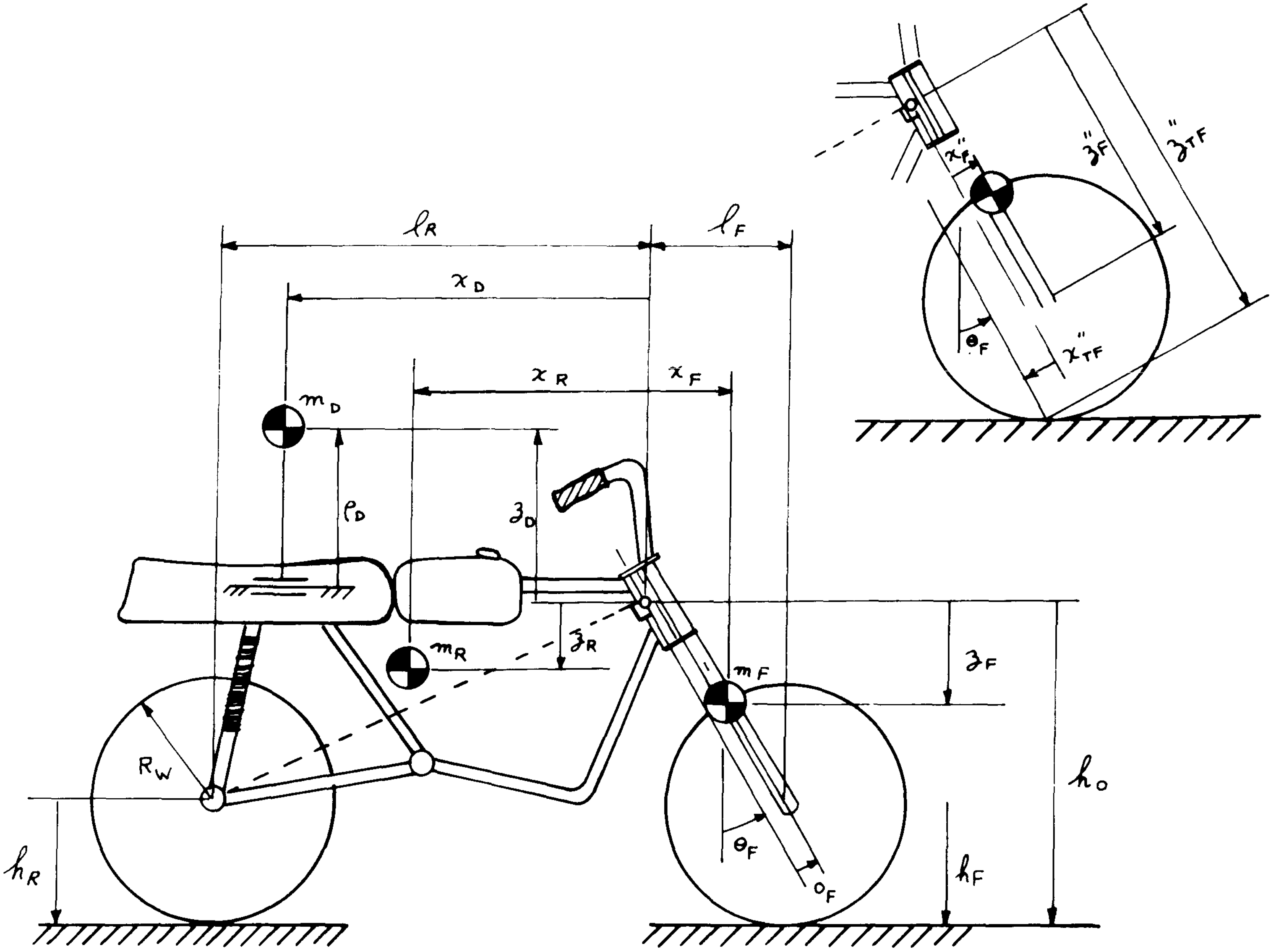


Figure 21 CHARACTERISTIC DIMENSIONS OF MINIBIKE MODEL

$$
\left[\begin{array}{c|c|c|c|c|c|c|c}
\Sigma M & 0 & 0 & 0 & \gamma_3 & -\gamma_2 & -y_F\cos\theta_F m_F & 0 \\ \hline
0 & \Sigma M & 0 & -\gamma_3 & & \gamma_1 & x''_F\cos\delta\, m_F & -\rho_D\cos\phi_D m_D \\ \hline
0 & 0 & \Sigma M & \gamma_2 & \gamma_1 & 0 & y_F\sin\theta_F m_F & y_D m_D \\ \hline
\begin{array}{l}\sin\theta_F\cos\theta_F\\ y_F m_F\end{array} &
\begin{array}{l}-z_R m_R\\ -\cos\theta_F z''_F m_F\\ -(z_D-\rho_D)m_D\end{array} &
\cos^2\theta_F\, y_F m_F &
\begin{array}{l}I_{RX}+z_R^2 m_R\\ +(\cos^2\delta I''_{FX}+\sin^2\delta I''_{FY})\\ \cos^2\theta_F-\sin\theta_F\cos\theta_F\cos\delta\\ I''_{FXZ}+(\cos\theta_F z''_F z_F\\ +\cos^2\theta_F y_F^2)m_F+z_D(z_D-\rho_D)m_D\end{array} &
\begin{array}{l}\cos\theta_F\sin\delta\cos\delta(I''_{FX}\\ -I''_{FY})+(\sin\theta_F\cos\theta_F z_F\\ -\cos^2\theta_F x_F)y_F m_F\\ -\cos\theta_F z''_F x_F m_F\end{array} &
\begin{array}{l}I_{RXZ}-x_R z_R m_R\\ -\sin\theta_F\cos\theta_F(\cos^2\delta I''_{FX}\\ +\sin^2\delta I''_{FY})-\cos^2\theta_F\\ \cos\delta I''_{FXZ}\ \sin\theta_F\cos\theta_F\\ y_F^2 m_F\ x_D(z_D-\rho_D)m_D\end{array} &
\begin{array}{l}-\cos\theta_F\cos\delta\\ (I''_{FXZ}\\ +x''_F z''_F m_F)\end{array} &
\begin{array}{l}\cos\phi_D\rho_D\\ (z_D-\rho_D)m_D\end{array} \\ \hline
\gamma_1 & 0 & -\gamma_1 &
\begin{array}{l}\cos\theta_F\sin\delta\cos\delta(I''_{FX}-I''_{FY})\\ -\sin\theta_F\sin\delta I''_{FXZ}\\ x_F y_F m_F\ I_{DXZ}\\ -x_D y_D m_D\end{array} &
\begin{array}{l}I_{RY}+(x_R^2+z_R^2)m_R+\sin^2\delta I''_{FX}\\ +\cos^2\delta I''_{FY}+(\sin\theta_F x_F\\ +\cos\theta_F y_F)z''_F m_F-(\sin\theta_F y_F\\ \cos\theta_F x_F\ \cos\delta x_F m_F\\ +I_{DY}+x_D^2 m_D+z_D(z_D\\ -\rho_D\{1-\cos\phi_D\})m_D\end{array} &
\begin{array}{l}-\sin\theta_F\sin\delta\cos\delta(I''_{FX}\\ -I''_{FY})-\cos\theta_F\sin\delta\\ I''_{FXZ}-z_F y_F m_F-I_{DXZ}\\ -y_D(z_D-\rho_D\{1-\cos\phi_D\})m_D\end{array} &
\begin{array}{l}-\sin\delta(I''_{FXZ}\\ +x_F z''_F m_F)\end{array} &
\begin{array}{l}-I_{DXY}\\ -x_D y_D m_D\end{array} \\ \hline
\begin{array}{l}-\sin^2\theta_F y_F m_F\\ -y_D m_D\end{array} &
\begin{array}{l}x_R m_R\\ +\sin\theta_F z''_F m_F\\ +x_D m_D\end{array} &
\begin{array}{l}-\sin\theta_F\cos\theta_F\\ y_F m_F\end{array} &
\begin{array}{l}-I_{RXZ}\ x_R z_R m_R+\sin^2\theta_F\\ \cos\delta I''_{FXZ}-\sin\theta_F\cos\theta_F\\ (\cos^2\delta I''_{FX}+\sin^2\delta I''_{FY})\\ -\sin\theta_F z_F z_F m_F-\sin\theta_F\cos\theta_F\\ y_F m_F-I_{DXZ}\ x_D z_D m_D\end{array} &
\begin{array}{l}-\sin\theta_F\sin\delta\cos\delta(I''_{FX}\\ -I''_{FY})\ \sin\theta_F(\sin\theta_F z_F\\ -\cos\theta_F x_F)y_F m_F\\ -I_{DYZ}-y_D z_D m_D\end{array} &
\begin{array}{l}I_{RZ}+x_R^2 m_R+\sin^2\theta_F\\ (\cos^2\delta I''_{FX}+\sin^2\delta I''_{FY})\\ +\sin\theta_F\cos\theta_F\cos\delta I''_{FXZ}\\ +(\sin\theta_F z_F x_F+\sin^2\theta_F\\ y_F^2)m_F+I_{DZ}+(x_D^2\\ +y_D^2)m_D\end{array} &
\begin{array}{l}\sin\theta_F\cos\delta\\ (I''_{FXZ}\\ +x''_F z''_F m_F)\end{array} &
\begin{array}{l}-I_{DXZ}\\ -\cos\phi_D x_D\\ \rho_D m_D\end{array} \\ \hline
-y_F\cos\theta_F m_F & x''_F\cos\delta\, m_F & y_F\sin\theta_F m_F &
\begin{array}{l}\sin\theta_F(I''_{FZ}+x''^2_F m_F)\\ -\cos\theta_F\cos\delta(I''_{FXZ}+x''_F z''_F m_F)\end{array} &
-\sin\delta(I''_{FXZ}+x''_F z''_F m_F) &
\begin{array}{l}\cos\theta_F(I''_{FZ}+x''^2_F m_F)\\ +\sin\theta_F\cos\delta(I''_{FXZ}+x''_F z''_F m_F)\end{array} &
I''_{FZ}+x''^2_F m_F & 0 \\ \hline
0 & \rho_D\cos\phi_D m_D & y_D m_D &
\begin{array}{l}I_{DX}+\cos\phi_D z_D\rho_D m_D\\ +y_D^2 m_D\end{array} &
\begin{array}{l}-I_{DXY}\\ x_D y_D m_D\end{array} &
\begin{array}{l}-I_{DXZ}\\ -\cos\phi_D x_D\rho_D m_D\end{array} &
0 & I_{DX}+\rho_D^2 m_D
\end{array}\right]
\cdot
\left[\begin{array}{c}
\dot{u}_o\\ \hline \dot{v}_o\\ \hline \dot{w}_o\\ \hline \dot{p}\\ \hline \dot{q}\\ \hline \dot{r}\\ \hline \ddot{\delta}\\ \hline \ddot{\phi}_D
\end{array}\right]
=
\left[\begin{array}{l}
\gamma_{11}+\gamma_{12}+\gamma_{13}+F_{XTR}+F_{XTF}\\ \hline
\gamma_{21}+\gamma_{22}+\gamma_{23}+F_{YTR}+F_{YTF}\\ \hline
\gamma_{31}+\gamma_{32}+\gamma_{33}+F_{ZTR}+F_{ZTF}\\ \hline
\begin{array}{l}pq I_{RXZ}+qr(I_{RY}-I_{RZ})+\cos\theta_F\cos\delta\beta_1+\cos\theta_F\sin\delta\beta_2+r\omega_R I_{WR}\\
-z_R\gamma_{21}-\cos\theta_F z''_F\gamma_{22}-\cos\theta_F y_F(\sin\theta_F\gamma_{12}+\cos\theta_F\gamma_{32})\\
-(z_D-\rho_D)\gamma_{23}-h_o F_{YTR}+\cos\theta_F\cos\delta(y''_{TF}F''_{ZTF}-z''_{TF}F''_{YTF})\\
-\cos\theta_F\sin\delta(z''_{TF}F''_{XTF}-x''_{TF}F''_{ZTF})-\sin\theta_F N''_{ZF}-N_{XD}\end{array}\\ \hline
\begin{array}{l}-(p^2-r^2)I_{RXZ}-pr(I_{RX}-I_{RZ})+\sin\delta\beta_1-\cos\delta\beta_2\\
-\cos\phi_D(p+\dot\phi_D)\dot\phi_D I''_{DXZ}+2\sin\phi_D\cos\phi_D q\dot\phi_D(I''_{DY}-I''_{DZ})\\
-(\cos\phi_D-\sin\phi_D)r\dot\phi_D(I''_{DY}-I''_{DZ})+(p\{p+\dot\phi_D\}-r^2)I_{DXZ}\\
-pq I_{DYZ}-pr I_{DZ}-r(p+\dot\phi_D)I_{DX}+qr I_{DXY}-x_R\gamma_{31}\\
+z_R\gamma_{11}-x_F\gamma_{32}+z_F\gamma_{12}-x_D\gamma_{33}+(z_D-\rho_D\{1-\cos\phi_D\})\gamma_{13}+h_o F_{XTR}\\
-\ell_R F_{ZTR}+\sin\delta(y''_{TF}F''_{ZTF}-z''_{TF}F''_{YTF})+\cos\delta(z''_{TF}F''_{XTF}-x''_{TF}F''_{ZTF})\end{array}\\ \hline
\begin{array}{l}-qr I_{RXZ}+pq(I_{RX}-I_{RY})-\sin\theta_F\cos\delta\beta_1-\sin\theta_F\sin\delta\beta_2\\
-\sin\phi_D(p+\dot\phi_D)\dot\phi_D I''_{DXZ}-(\cos\phi_D-\sin\phi_D)q\dot\phi_D(I''_{DY}-I''_{DZ})\\
-2\sin\phi_D\cos\phi_D r\dot\phi_D(I''_{DY}-I''_{DZ})+(p\{p+\dot\phi_D\}-q^2)-pq I_{DY}+pr I_{DYZ}\\
+q(p+\dot\phi_D)I_{DX}-qr I_{DXZ}-p\omega_R I_{WR}+x_R\gamma_{21}+\sin\theta_F z''_F\gamma_{22}\\
-\sin\theta_F y_F(\sin\theta_F\gamma_{12}+\cos\theta_F\gamma_{32})+x_D\gamma_{23}-y_D\gamma_{13}+\ell_R F_{YTR}\\
-\sin\theta_F\cos\delta(y''_{TF}F''_{ZTF}-z''_{TF}F''_{YTF})+\sin\theta_F\sin\delta(z''_{TF}F''_{XTF}-x''_{TF}F''_{ZTF})-\cos\theta_F N''_{ZF}\end{array}\\ \hline
\begin{array}{l}q''(r''+\delta'')I''_{FXZ}-p''q''(I''_{FX}-I''_{FY})-x''_F(\cos\theta_F\sin\delta\gamma_{12}-\cos\delta\gamma_{22}\\
\sin\theta_F\sin\delta\gamma_{32}+eF''_{YTF}-p''\omega_F I_{WF}+N''_{ZF}\end{array}\\ \hline
\begin{array}{l}\cos\phi_D I''_{DXZ}q\dot\phi_D+\sin\phi_D I''_{DXZ}r\dot\phi_D-I_{DXZ}q(p+\dot\phi_D)-I_{DYZ}(q^2-r^2)\\
+I_{DXY}r(p+\dot\phi_D)+(I_{DZ}-I_{DY})qr-\cos\phi_D\rho_D\gamma_{23}+y_D\gamma_{33}+N_{XD}\end{array}
\end{array}\right]
$$

Figure 22 MATRIX EQUATION OF MOTION

rider steer control.

The rider model incorporates human operator characteristics which have been developed in theoretical studies of manual control as utilized here. The human operator outputs are steering torque and rider lean torque, with inputs of vehicle roll angle, roll velocity and roll acceleration. Space path coordinates are related to vehicle position and direction of motion. Also included are rider reaction time delay and lag compensation.

Forty-four input data are required by the simulation program. These data include dimensions, weights, moments of inertia, tire side force coefficient, initial conditions, etc. Figure 23 is a listing of typical input data.

The digital computer bicycle simulation program basically consists of the application of a modified Runge-Kutta step-by-step procedure to integrate equations of motion. The integration step size is variable although a value of 0.01 second is generally used. With a step size of 0.01 second, solutions up to 10 seconds duration (problem time) may be obtained. Solution output is obtained from a separate output processor program which can produce time histories of as many as 36 variables (bicycle translational and angular positions, velocities, accelerations, and tire force components, etc.) in both printed and plotted format. A fundamental objective of Calspan's research program in two-wheel vehicle dynamics is the ultimate use of the computer simulation as a design tool. Maneuvers or riding situations

```
WHEELBASE (IN)                                         41.50

TOTAL WEIGHT OF BICYCLE (LB)                           40.90

LOCATION OF TOTAL BICYCLE C.G.                         18.05
FORWARD OF REAR WHEEL CENTER (IN)

LOCATION OF TOTAL BICYCLE C.G.                         20.76
ABOVE GROUND (IN)

ROLL MOMENT OF INERTIA OF THE TOTAL BICYCLE            12.64
ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)

PITCH MOMENT OF INERTIA OF THE TOTAL BICYCLE           35.95
ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)

YAW MOMENT OF INERTIA OF THE TOTAL BICYCLE             25.70
ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)

ROLL-YAW PRODUCT OF INERTIA OF THE TOTAL BICYCLE       -1.62
ABOUT AXIS THROUGH TOTAL C.G. (LB-IN-SEC SQ)
```

```
WEIGHT OF FRONT FORK ASSEMBLY                          11.40
(FORK,WHEEL,AND HANDLE BARS),(LB)

PERPENDICULAR DISTANCE FROM C.G. OF FRONT               1.50
FORK ASSEMBLY TO STEER AXIS (IN)

DISTANCE PARALLEL TO STEER AXIS FROM C.G. OF            9.50
FRONT FORK ASSEMBLY TO FRONT WHEEL CENTER (IN)

ROLL MOMENT OF INERTIA OF FRONT FORK
ASSEMBLY ABOUT AN AXIS PERPENDICULAR TO THE             4.59
STEER AXIS THROUGH C.G. OF ASSEMBLY (LB-IN-SEC SQ)

PITCH MOMENT OF INERTIA OF FRONT FORK
ASSEMBLY ABOUT AN AXIS THROUGH THE C.G.                 5.56
OF THE ASSEMBLY (LB-IN-SEC SQ)

YAW MOMENT OF INERTIA OF FRONT FORK                     1.86
ASSEMBLY ABOUT THE STEER AXIS (LB-IN-SEC SQ)

ROLL-YAW PRODUCT OF INERTIA OF FRONT
FORK ASSEMBLY ABOUT AN AXIS THROUGH                    -0.32
THE C.G. OF THE ASSEMBLY (LB-IN-SEC SQ)
```

```
WEIGHT OF RIDER (LB)                                  102.00

LOCATION OF RIDER C.G. FORWARD                         11.30
OF REAR WHEEL CENTER (IN)

HEIGHT OF RIDER C.G. ABOVE GROUND (IN)                 46.60

HEIGHT OF SADDLE ABOVE GROUND (IN)                     38.20

ROLL MOMENT OF INERTIA OF RIDER ABOUT                  27.80
AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)

PITCH MOMENT OF INERTIA OF RIDER ABOUT                 33.90
AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)

YAW MOMENT OF INERTIA OF RIDER ABOUT                   18.40
AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)

ROLL-YAW PRODUCT OF INERTIA OF RIDER ABOUT              0.0
AN AXIS THROUGH HIS C.G. (LB-IN-SEC SQ)
```

```
CASTER ANGLE OF THE STEER AXIS (DEG)                   21.00

FORK OFFSET (IN)                                        1.87

UNDEFLECTED WHEEL ROLLING RADIUS (IN)                  13.62

TIRE SECTION WIDTH (IN)                                 1.60

RADIAL STIFFNESS OF TIRE (LB/IN)                      710.00

SPIN MOMENT OF INERTIA OF THE FRONT                     1.76
WHEEL (LB-IN-SEC SQ)

SPIN MOMENT OF INERTIA OF THE REAR                      1.76
WHEEL (LB-IN-SEC SQ)


FIRST AND SECOND ORDER COEFFICIENTS RELATING            0.32
TIRE SIDE FORCE AND SLIP ANGLE                          0.02

FIRST AND SECOND ORDER COEFFICIENTS RELATING            0.01
TIRE SIDE FORCE AND INCLINATION ANGLE                   0.0

COEFFICIENT OF ROLLING RESISTANCE (LB/LB)               0.0

AERODYNAMIC DRAG COEFFICIENT (LB/MPH-SQ)                0.0
```

```
INITIAL X LOCATION (FT)                                 0.0

INITIAL Y LOCATION (FT)                                 0.0

INITIAL YAW ANGLE (DEG)                                 0.0

INITIAL FORWARD VELOCITY (MPH)                         15.00

MAXIMUM ROLL ANGLE (DEG)                               60.00

MAXIMUM PATH DISTANCE (FT)                             70.00

MAXIMUM SIMULATION TIME (SEC)                           0.50

INTEGRATION TIME INCREMENT (SEC)                        0.01
```

Figure 23 TYPICAL INPUT DATA FOR COMPUTER SIMULATION PROGRAM would be simulated in which the resultant motions of the vehicle could be employed to determine the effect of specific design parameter changes on stability and maneuverability.

The simulation program, consisting of seven subroutines, uses approximately 110 K bytes of core storage and requires about 6 seconds of Central Processing Unit time per second of problem time when run on an IBM 370-165 computer. The output processor program uses approximately 160 K bytes of core storage and requires about 5 seconds of Central Processing Unit time per typical run. The total cost of both the simulation and output processor programs is approximately seven dollars per problem.

Application to Minibike Analysis

The computer simulation was used in this program primarily to demonstrate its applicability to studying the stability of the rider-minibike system. The stability of several minibike configurations was investigated in two simulated situations:

1. Control response: developing a steady-state turn from a straight path
2. Disturbance response: re-establishing roll equilibrium after a side force disturbance

In the first task the initial conditions of the minibike were designated as straight line travel at a constant velocity of 10 mph. The input to the rider model was a requirement for an immediate change to a steady state turn at a roll angle of 20 degrees. In the second task the minibike was initially moving in a straight line at 10 mph. The input was a 16 pound side force disturbance applied for 1.1 seconds to the minibike. The force was applied at a point near the center of the wheelbase and 23 inches above the ground.

Since the Charger minibike best represented the average of the six minibikes used in this program, its physical characteristics were selected as the base configuration for its simulation runs. Table 9 gives the characteristics of this reference configuration.

Five minibike parameters were studied:

1. caster angle
2. fork offset
3. wheelbase
4. weight
5. rider weight distribution

Simulation runs were made with two variations of each parameter-one greater and one less than the reference configuration values. The parameter variations used in this study (see Table 9) represent the range of measured values from the test group.

Figure 24 shows the time histories of steer and roll angles for the control response tests. The desired steady state roll angle in these runs was 20 degrees. Table 9 shows the steady state roll angle achieved for each minibike configuration and the time to reduce the roll velocity to less than 0.5 degree

Table 9

RESULTS OF SIMULATED MINIBIKE PARAMETER STUDY

	CONTROL RESPONSE TEST		DISTURBANCE RESPONSE TEST		
MINIBIKE CONFIGURATION	STEADY STATE ROLL ANGLE (deg.)	TIME TO REDUCE ROLL VELOCITY TO 0.5 deg/sec (sec.)	YAW ANGLE DEVIATION (deg.)	STEER ANGLE CORRECTION (deg.)	ROLL ANGLE DEVIATION (deg.)
BASE CONFIGURATION*	18.6	3.2	5.3	5.5	7.4
15° CASTER ANGLE	14.3	2.9	12.3	6.8	10.2
35° CASTER ANGLE	26.0		-2.5	3.8	4.3
ZERO FORK OFFSET	8.6	5.5	21.5	11.3	16.2
3.0 in. FORK OFFSET	DIVERGENTLY UNSTABLE		-12.6	-2.2	-1.7
30 in. WHEELBASE	18.3	3.3	7.7	4.8	7.7
42 in. WHEELBASE	19.0	3.2	3.1	6.0	7.2
50 POUND MINIBIKE WEIGHT	17.8	3.1	5.2	5.7	7.8
120 POUND MINIBIKE WEIGHT	18.9	3.3	5.2	5.2	7.2
20% FRONT/80% REAR RIDER WEIGHT DISTRIBUTION	17.8	3.2	7.3	6.5	8.7
60% FRONT/40% REAR RIDER WEIGHT DISTRIBUTION	20.0	3.0	0.7	3.2	4.8

*24.2 deg. CASTER ANGLE, 1.38 in. FORK OFFSET, 36 in. WHEELBASE, 95.5 POUND WEIGHT, AND 31% FRONT/69% REAR RIDER WEIGHT DISTRIBUTION.

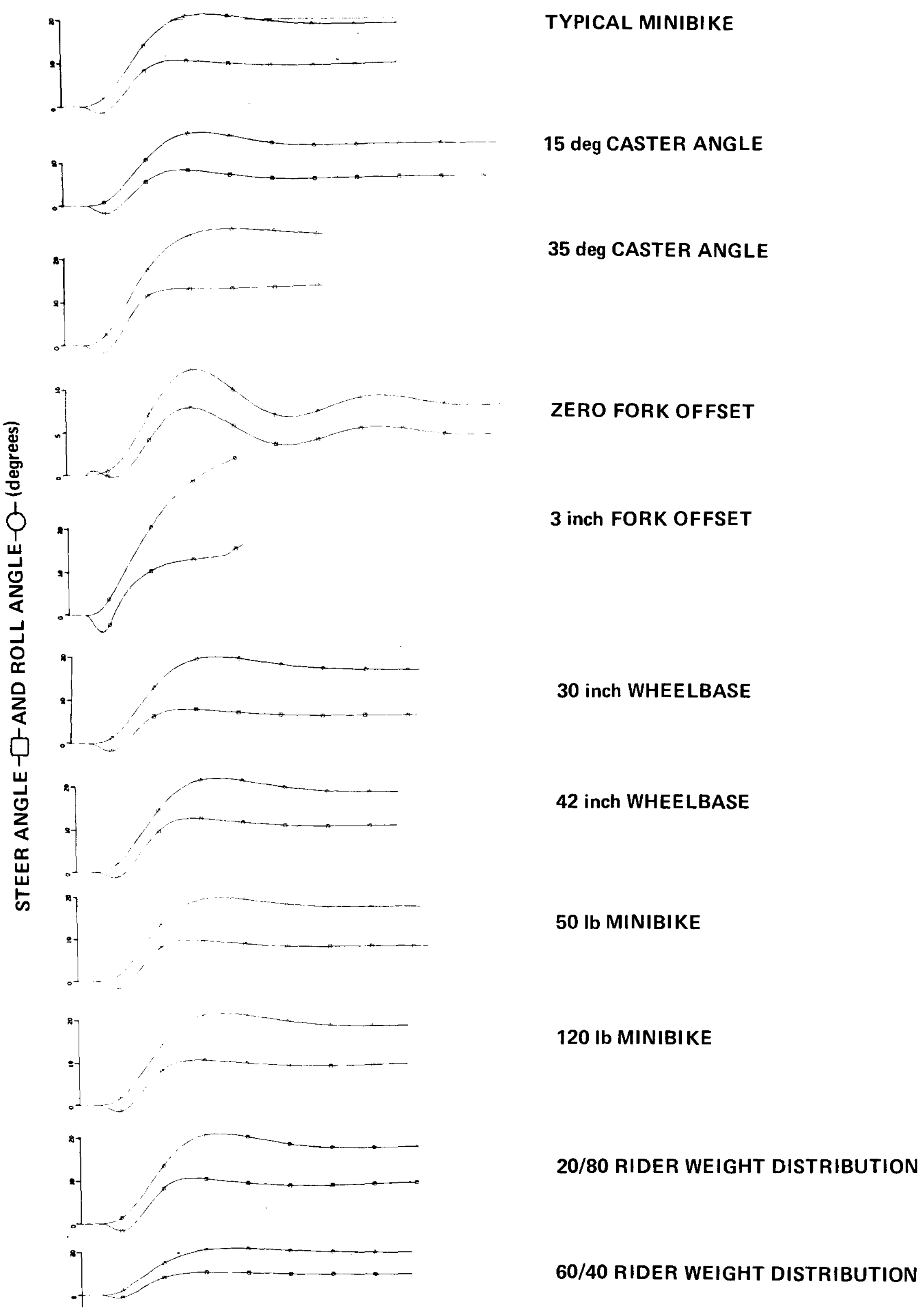


Figure 24 MINIBIKE CONTROL RESPONSE SIMULATION RUNS

per second (time to damp the roll oscillation). Since the rider model has constant characteristics, differences in minibike control requirements are reflected as differences in the steady state roll angle and transient response. In the run with 3 inches of fork offset, the steering trail became negative, resulting in negative steer restoring torques and unstable performance (since the rider model had no compensatory capability).

It is obvious from these results that, of parameters studied, the caster angle and fork offset have the greatest influences on stability. Wheelbase, minibike weight, and rider weight distribution had little effect in this test.

The simulated disturbance response test was developed from a full scale test in which rocket motors were used to create an artificial side wind gust. The full scale tests were performed with the rider tracking a straight line at 10 mph. Motion picture coverage of the full scale disturbance response shows good qualitative correlation for steer and roll angles with the simulation run with the Charger characteristics.

The simulated rider did not try to track a straight path but operated only to return the minibike to the vertical equilibrium position. Hence, there generally was a deviation in the final yaw angle relative to the initial straight path. Table 9 shows the yaw angle deviation as well as the magnitudes of the required steer correction and maximum roll angle deviation. Time histories of steer and roll angles are shown in Figure 25.

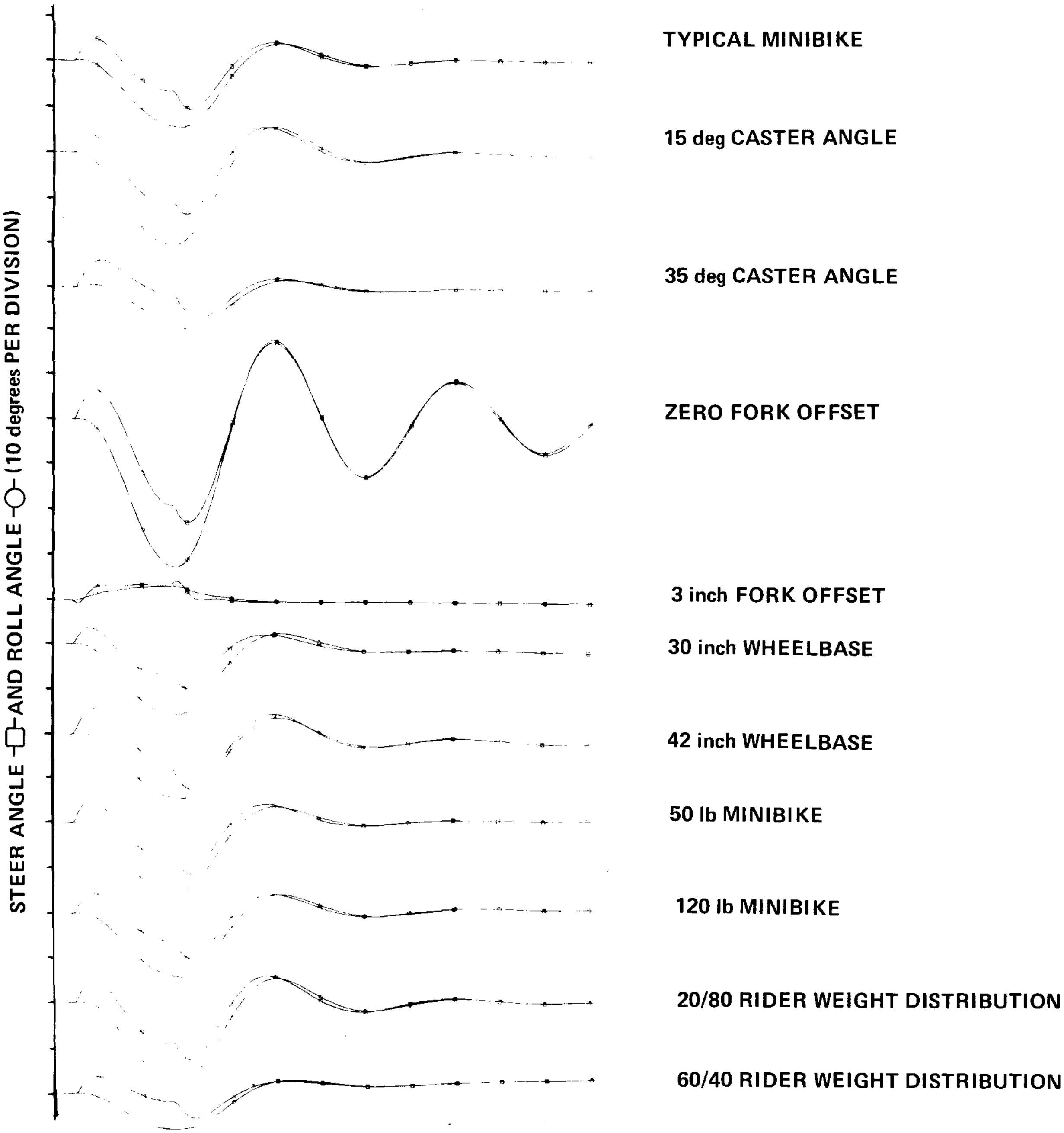


Figure 25 MINIBIKE DISTURBANCE RESPONSE SIMULATION RUNS

4.0 SAFETY STANDARDS RECOMMENDATIONS

This section is aimed at placing the results of the studies performed during the program in appropriate perspective for use in formulating safety standards. Our evaluations of these results and the conclusions which we have drawn are presented in terms of general recommendations on various design and operational characteristics of tricycles and minibikes which should be considered by the FDA in its development of these standards.

The major problem in translating the findings of this study into useful specifications for the improvement of tricycle and minibike operational safety lies in being able to define objective performance standards. It is very easy to be trapped into phrasing standards in design terms, resulting in standards which not only may be ineffective in ruling out poorly performing units but which may also compromise the development of new and better designs. Although we have not been able to suggest numerical values for requirements in all cases, a strong effort has been made to cast our recommendations in this framework.

The study has been restricted to those aspects of total design which are directly concerned with stability and controllability. In this regard, matters of structural strength and design (material gauges, joining methods, quality control of assembly, etc.) have not been of primary concern. However, to the extent that these factors impinge on the safety of operation (a good example would be a foot rest peg which can dig into the road surface in hard cornering), they have been identified and commented upon.

4.1 Tricycles

There would seem to be two over-riding considerations in postulating regulations for the design of tricycles with regard to stability - they should be objective (i.e., numerical) and they should be performance-oriented(i.e., compliance should be demonstrable by test). With these as prerequisites, our recommendations are offered as foundations for tricycle stability and performance standards. It is recognized that these must be reviewed within a broader framework of associated factors (cost of manufacture, cost to consumer, structural strength, etc.)

It should be recognized that this study of fundamental safety requirements of tricycles could not encompass all of the myriad of designs available in the market. A conscientious effort was made to obtain a representative sample of six units on which to base the study and from which it was reasonable to expect identification of critical safety qualities. From observations and test results with these units, it has been determined that the following items deserved review.

Rollover immunity
Seat height adjustibility
Rear axle step bar
Steering
Speed and Braking

Rollover Immunity

The concept of a rollover stability parameter and the existence of a critical value for each set of operating conditions is not difficult to understand. Its use in conjuction with a safety standard poses a number of questions, however. What is a reasonable margin of safety to apply in a standard? How should the standard be worded to avoid suppressing future design ideas that are acceptable (on a performance basis) but may be compromised by the wording? Can a simple, safe, and unambiguous performance test be devised. In this regard, our recommendations are:

1. The standard should require demonstration of compliance to a requirement which might be stated as -

> The test unit shall not rollover (tipover) at a speed of ___ feet/sec. (mph) on a circular path with radius of___ feet. The test shall be performed on a level surface with an equivalent rider weight of pounds rigidly attached to the seat as shown in Figure ___.

The Bureau's problem is then to determine values to be inserted in the blank spaces and to devise detailed instructions for performing the test. These instructions would cover requirement for settings of adjustable components, alternate values for speed and radius if test units are incapable of the specified values, means for performing the test, etc. Note that the test can be safely performed with a human rider if the unit can comply. The burden is then on the manufacturer to produce a design (his perogative) which will perform satisfactorily. (BPS's right to specify)

2. Alternatively, the Bureau could require that the manufacturer provide the consumer with information on the roll-over stability of the product. This information could be in the form of the stability parameter and operational range of the unit. BPS could compile these data for all products on the market and make this information publicly available.*

Seat Height Adjustibility

It is recommended that the standard incorporate a requirement for fixed seat height. The seat should be firmly and permanently attached to the rear frame assembly.

Rear Axle Step Bar

It is recommended that the standard attempt to discourage double-riding. Rear axle protection and/or frame structural stiffness should be accomplished by means which inhibit their use by a passenger. It is our opinion that the rider who needs to use the step bar in order to mount the tricycle is not properly matched to the unit and should not be aided in trying to ride it.

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* There is a precedence for this in the Consumer Information required by the National Highway Transportation Safety Administration on Automobiles.

Steering Assembly

It is recommended that steering motion be limited. It may not be reasonable to fix an absolute value for front wheel motion but allowable motion might be related to wheelbase as a function of a minimum value for turn radius. Based on our observations during testing, a minimum turn radius of 5 feet provided ample maneuverability of the test units for outdoor play.

Speed

We do not recommend specification of maximum speed for direct-drive pedal-powered units. Rather, we believe that speed should be related to other operational and design factors through a rollover immunity specification. However, the Bureau should be cognizant of the possibilty that designs utilizing indirect drives (chain and sprocket systems, for example) which are capable of higher speeds than currently available units may be marketed and that these may require special study. In that case, the need for speed-limiting (or, at least, review of the ramifications of higher speed on safety) should be re-examined.

Brakes

We do not believe that brakes are necessary, or even desirable, on vehicular toys employing direct-drive rider-developed power for propulsion and having maximum speeds of less than 10 mph. Observations made during the test program indicate satisfactory stopping ability for all units <u>if</u> the rider maintains foot contact with the pedals. Nevertheless, one can conceive of units with high-inertia driven wheels (for which the rider's leg strength is inadequate in braking) and it is recommended that the Bureau consider the need for specifying limits on such vehicles.

The role of maintenance in operational safety cannot be overemphasized. Many of the injuries reported by NEISS are directly traceable to faulty equipment - missing pedals, loose handlebars, broken sharp edges. While recognizing that good design practices should be aimed at minimizing the susceptibility of equipment to such impairments and that this represents an obligation on the part of the manufacturer, we suggest that an equal obligation resides with the parent to ensure that the tricycle is in a reasonable operating condition. We recommend that BPS consider the following avenues for emphasizing this aspect of the problem -

1. Preparation of a booklet pointing out the hazards of operating tricycles on steep grades (runaway speeds can quickly become unmanageable), of being pushed on a tricycle (particularly by adults), of riding double, and of using a unit with defective or missing parts. The booklet might also stress the importance of a wide rear track, a low comfortable seat, well-designed pedals, etc.

2. Requiring the manufacturer to provide each unit offered for sale with recommendations on the ranges of rider weight and stature for which the unit is suited.

4.2 Minibikes

Extensive full-scale testing and analysis of minibike performance suggests that the following items should be considered by the BPS in formulating safety standards.

Braking*

There are several features of brake performance which merit attention. These are:

1. Stopping distance (or deceleration). Satisfactory braking should be demonstrated by full-scale tests. Since vehicle speed greatly affects stopping distance, the braking deceleration requirement should be graduated with respect to the maximum speed of the minibikes. Based on our test results we recommend that an average decleration of approximately 0.5 g (stopping distance of about 53 feet) should be required for minibikes with a speed capability of 28 mph. If stopping distance was required to vary linearly with maximum speed, then a stopping distance in feet (from the maximum speed) numerically equal to twice the maximum speed in mph would give 56 feet (a deceleration of about 0.47g) from 28 mph.

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* Minibike braking specifications should be consistent in form with those now under development by BPS for bicycles.

Furthermore, for maximum speeds of 15 mph the stopping distance would be 30 feet (or 0.25g) which is the BMA-6 braking performance standard for bicycles with rear brakes only. Test conditions should specify test surface (dry, flat, free from surface dirt, brushed concrete or equivalent) and rider weight.

2. Rider-applied brake control force. Control forces should be compatible with the strength capabilities of the probable rider group. In addition, at least a qualitative requirement that abrupt lockup of the brake shall not occur should be imposed. Values for this specification should be available from other current BPS studies.

3. The standard should incorporate some restriction on front wheel lockup for units equipped with front wheel brakes.

Tires

Minibike performance is very sensitive to tire inflation pressure. In spite of this, few minibike tires are labelled with manufacturer's recommended pressures. It is recommended that the standards require such labelling - perhaps given as a range of pressures, with separate instructions to indicate selection as a function of rider weight and usage.

Cornering

Cornering capabilities of the machine should be demonstrated in performance tests. In particular, the standard should militate against any frame element such as foot pegs and kick stands which scrub the surface at bank angles within the vehicle's operating range. We recommend, as a preliminary value, that this angle be at least 45 degrees. Frame elements specifically designed to prevent rider injury in skids (i.e., skid plates, etc.) are excluded from this requirement.

Suspension

Our test results indicate a strong relationship between rear suspension design and reduction in safety of operation over uneven terrain. It is recommended that the minibike standards require all suspensions to incorporate damping. Demonstration of compliance would require full-scale tests of a seated rider traversing a bump of specified geometry at a specified speed without losing seat contact. Although this is recognized as a severe test, the potential for accident with novice riders on inferior designs justifies this recommendation. The Bureau would be expected to provide detailed test procedures for performing this test to the manufactureres. A reasonable starting point would be the procedure used in this program.

Acceleration

Our full scale tests demonstrated that certain minibikes had acceleration characteristics which caused rear pitch-over during wide open throttle starts. The standard should incorporate restrictions on acceleration characteristics which cause such inadvertent wheelies. Safe acceleration should be demonstrated in performance tests (using mechanical pitch-over restraints, front wheel lift-off sensing ignition cut outs, etc.

to restrict pitch-over in case of failure of the test units to comply). Test conditions should specify "worst case" rider weight, stature and position, and test surface (i.e., a high friction surface which prevents wheel spin).

Handling

The effects of several minibike parameters (caster angle, steering trail, wheel size, etc.) on handling characteristics have been investigated in the experimental and analytical studies performed in this program. Certain parameters have been identified as being significant but, as yet, there is not a sufficient data base to permit quantitative specification of requirements for these factors in a safety standard. Clearly, more work needs to be performed to establish the limits of permissable tradeoffs among these interacting parameters to assure adequate stability and control of the unit. CAL is currently engaged in research on two-wheel vehicle handling which is aimed at just such determinations. In addition to these analyses, procedures for testing must be developed, and objective measurements and quantitative performance requirements must be specified.

5.0 REFERENCES

1. Rice, R.S. and Roland, R.D., An Evaluation of the Performance and Handling Qualities of Bicycles, CAL Report No. VJ-2888-K, 1970.

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Appendix A

Tricycle Rollover Stability Boundary

The objective of this analysis is to derive an expression for the limiting operating conditions at which a tricycle will remain upright when cornering. This expression, which relates the physical design of the tricycle to the characteristics of the turn (i.e., speed, turn radius, etc), can then be used to define boundaries for safe operation.

The significant parameters of the problem are identified in Figure A-1 where the symbols are as defined below.

a: Distance from the ground contact point of the front wheel to the center-of-gravity of the rider-tricycle combination

b: Distance from the ground contact points of the rear wheels to the center-of-gravity of the rider-tricycle combination

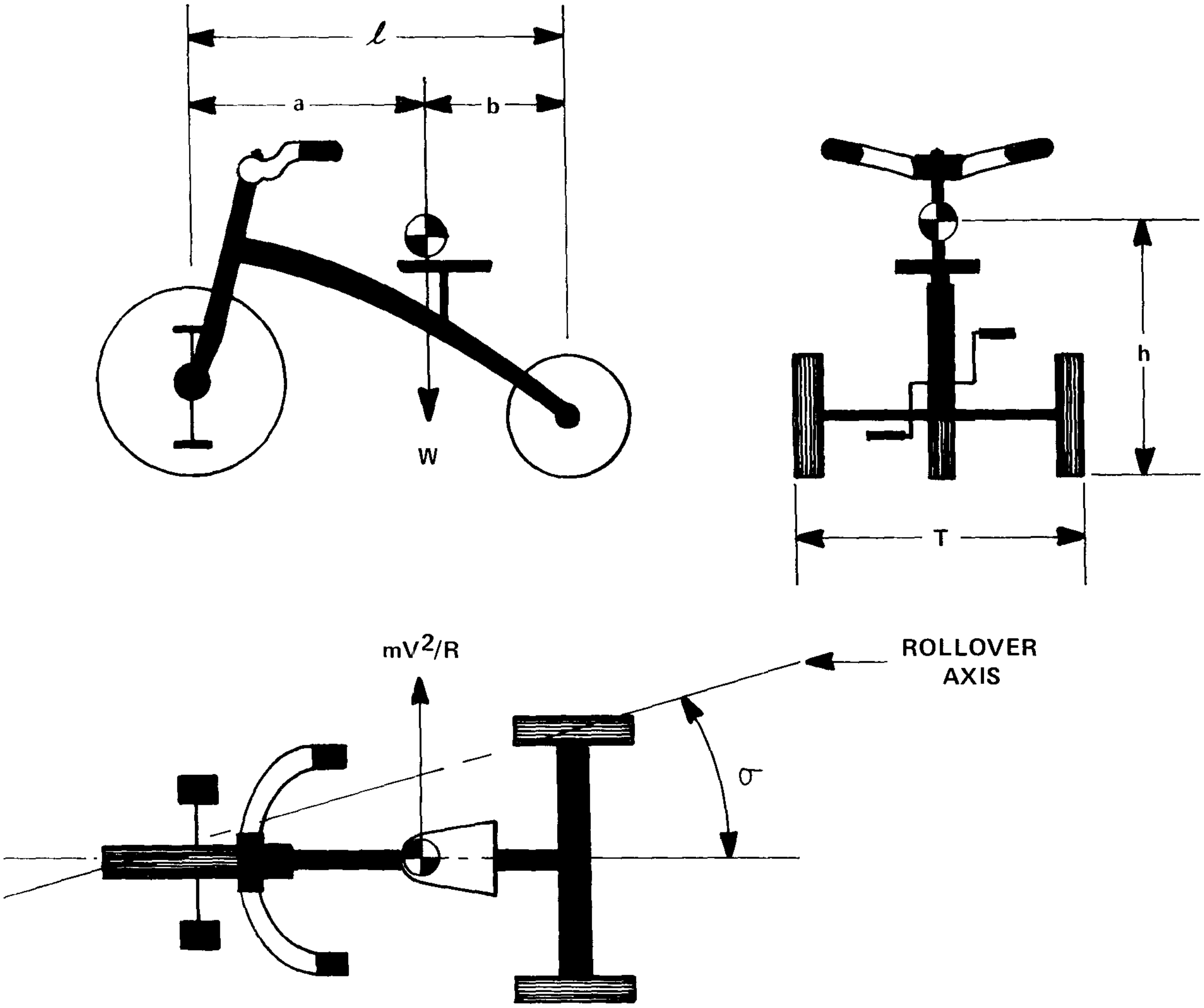
h: Distance of the center-of-gravity of the rider-tricycle combination above the ground plane

l: Tricycle wheelbase

m: Mass of the rider-tricycle combination (equal to the weight of the combination, W, divided by the gravitational constant, g.)

R: Radius of turn

T: Overall track width of tricycle at rear wheels (the distance between the outside edges of the rear wheels)



R = RADIUS OF TURN
UPSETTING FORCE: $m V^2/R$
RESTORING FORCE: $W = mg$

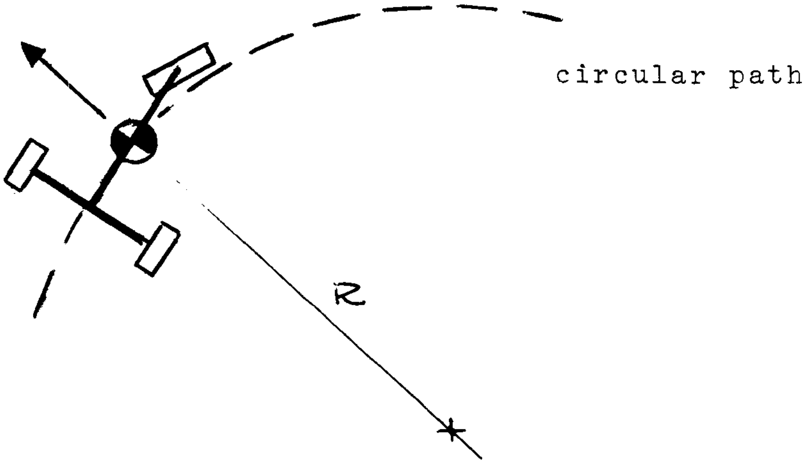
Figure A-1 CHARACTERISTIC DIMENSIONS OF TRICYCLE MODEL

V: Tricycle speed

σ: Angle between the longitudinal centerline of the tricycle and a line connecting the front wheel contact point and the contact point of one of the rear wheels. (This line is the rollover axis)

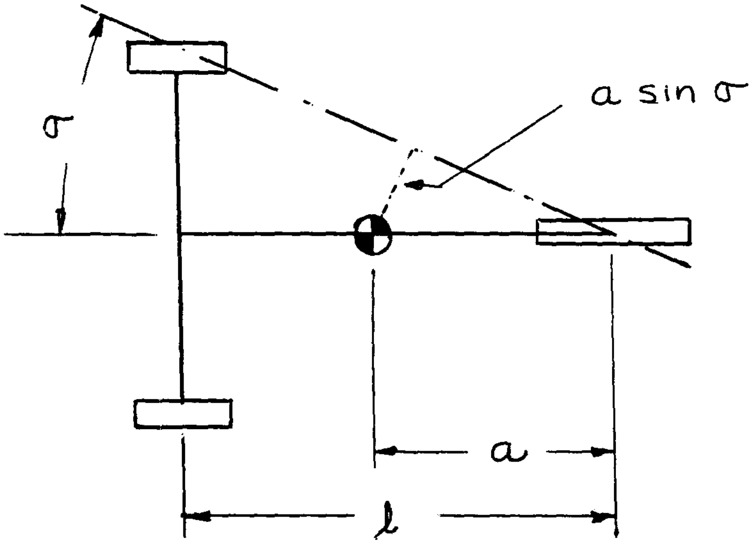
Two primary forces are also identified in the figure - an upsetting force, due to the centrifugal force (which is generated when the tricycle is on a curved path) and a restoring force (the weight of the rider-tricycle combination). Overturning can occur when the moment around the rollover axis resulting from the upsetting force exceeds the restoring moment about this axis.

First consider the upsetting moment. The centrifugal force acts at the c.g. of the system in a radial direction as shown in the sketch below.



Using the symbols of Figure A-1, the moment about the longitudinal centerline of the tricycle is $\frac{mV^2h}{R}$. The rollover axis, however, lies at an angle of σ with respect to the centerline, and the moment about this axis is therefore - $M_U = \frac{mV^2h}{R} \cos\sigma$

The magnitude of the restoring moment is determined by the weight of the rider and tricycle acting at a radius arm illustrated in the sketch below. This arm is equal to a $\sin\sigma$.



Thus, the restoring moment is - $M_R = mga \sin\sigma$.

When M_R is greater than M_U , the tricycle will remain upright in a turn. Therefore, M_R may be compared with M_U to define a rollover stability boundary -

$$mga \sin\sigma > \frac{mV^2h}{R} \cos\sigma$$

This reduces to - $\frac{a}{h} \tan\sigma > V^2/gR$

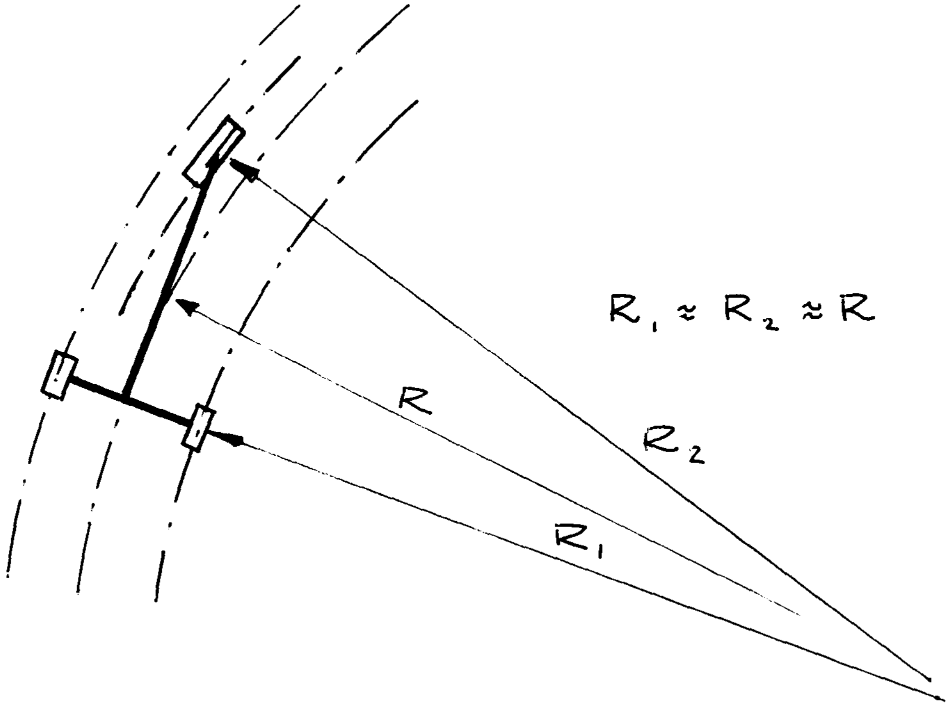
where the physical characteristics of the rider and tricycle are described by the terms on the left and the operating conditions by the terms on the right. From Figure A-1, it is apparent that $\tan\sigma = \frac{T}{2\ell}$; so a very useful form of the equation for the rollover stability boundary becomes -

$$\frac{aT}{2h\ell} = V^2/gR$$

Note that the rider-tricycle mass term no longer appears explicitly in the expression. Both rider weight and tricycle weight have, however, effects on the values of a and h. Note further, that the right hand term is simply the lateral acceleration of the vehicle (in g units).

For certain purposes, it is desirable to replace the radius of curvature term, R, with an equivalent steering angle term. As shown in the sketch, the wheels of a three-wheeled vehicle follow three separate tracks in negotiating a constant radius turn at very low speed. The center of the circular arc which is described is at the intersection of the extensions of the rear axle and front wheel hub. The steering angle, δ, is simply related to the radius by - $\delta = \tan^{-1}\frac{\ell}{R}$

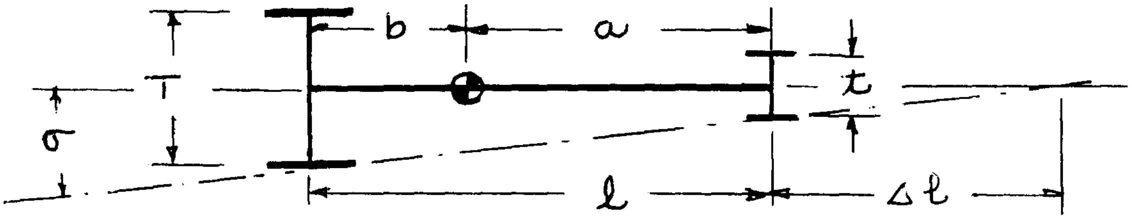
or, when $R \gg \ell$, $\delta = \ell/R$



Since the solid tires of tricycles operate at only very small slip angles in cornering at all practical speeds, a reasonable approximation for the rollover stability equation may be obtained with the substitution of $R = \frac{\ell}{\delta}$. Then -

$$\frac{aT}{2h} = \frac{V^2}{g}\delta$$

Units having two front wheels (i.e., having a non-zero front track width) may be treated in a similar way by modifying the effective value of the restoring moment arm. This design may be analyzed with the aid of the sketch shown below.



The angle σ can be defined by a number of measurements-

$$\tan \sigma = \frac{T-t}{2\ell} = \frac{T}{2(\ell+\Delta\ell)} = \frac{t}{2\Delta\ell}$$

The restoring moment is-

$$(a+\Delta\ell)\sin\sigma \times W$$

Since $\Delta\ell = \frac{t}{2}\cot\sigma$, the moment arm may also be written as -

$$\frac{t}{2}\cos\sigma + a\sin\sigma$$

and the restoring moment is -

$$M_R = mg\left(a\sin\sigma + \frac{t}{2}\cos\sigma\right)$$

The upsetting moment is the same as for the 3-point contact unit -

$$M_U = \frac{mV^2h}{R}\cos\sigma$$

The incipient rollover condition (M_R=M_U) is-

$$mg\left(a\sin\sigma + \frac{t}{2}\cos\sigma\right) = \frac{mV^2h}{R}\cos\sigma$$

or -

$$a\tan\sigma + \frac{t}{2} = V^2h/gR$$

As indicated above, $\tan\sigma = \frac{T-t}{2\ell}$, so -

$$a\frac{T-t}{2h\ell} + \frac{t}{2h} = V^2/gR$$

which may also be written as -

$$\frac{aT}{2h\ell} + \frac{t}{2h}\left(1-\frac{a}{\ell}\right) = V^2/gR$$

Thus, the restoring moment of the 3-point contact unit (characterized previously by $\frac{aT}{2h\ell}$) is augmented in the 4-point contact vehicle by $\frac{t}{2h}(1-\frac{a}{\ell})$. This equation has general application; it reduces to $\frac{aT}{2h\ell}$ for 3-point units and to $\frac{t}{2h}$ for 4-point vehicles with equal front and rear tracks.

Finally, it is desirable to move the constant factor of 1/2 from the terms concerned with design to the operational terms. Thus, the rollover stability boundary may be defined as -

$$\frac{aT}{\ell h} = \frac{2V^2}{g\mathcal{R}} \qquad \text{(for 3-wheel units)}$$

$$\frac{aT}{\ell h} + \frac{t}{h}\left(1 - \frac{a}{\mathcal{L}}\right) = \frac{2V^2}{g\mathcal{R}} \qquad \text{(for 4-wheel units)}$$

Appendix B

Tricycle Pitchover Stability Boundary

Tricycles *should* afford the rider a certain level of rollover stability so that turns can be made by the novice rider with reasonable confidence. But they *must* provide a satisfactory measure of pitchover stability to assure safe operation in normal play on sloped driveways and sidewalks, particularly with passengers on the rear axle step. The evaluation of this aspect of operation can be best appreciated by an analysis based on Figure B-1. This figure is similar to a portion of Figure A-1 and the symbols used here are identical.

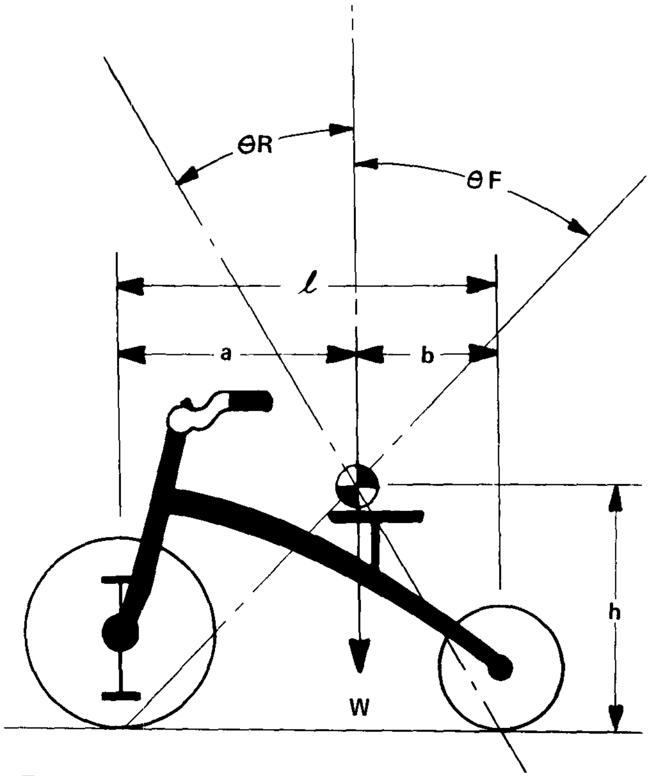


Figure B-1 PITCHOVER ANALYSIS MODEL

The weight of the rider-bicycle combination is reacted at the ground contact points according to the equation -

$$W_T = \underset{\text{(front)}}{\frac{b}{\ell} W_T} + \underset{\text{(rear)}}{\frac{a}{\ell} W_T}$$

Two angles are identified -

$$\theta_F = \tan^{-1} a/h$$

$$\theta_R = \tan^{-1} b/h$$

and these are the static pichover angles for the combination. That is, they are the angles of surface slopes at which the tricycle will tend to pitch over when it faces downhill and uphill, respectively. Since tricycles are not ordinarily equipped with brakes, pitching moments due to longitudinal declerations are of little consequence in normal operation. Acceleration effects are also small since the riders connot generate sufficient pedal torque to cause problems. Hence, the primary conditions of concern with respect to pitchover are double-riding and curb-climbing.

Appendix C

Physical Characteristics and Performance Capabilities of Tricycle Riders

The potential tricycle rider group is taken as all children between the ages of one and six years and the analyses must therefore account for a wide spread in rider size and weight. In order to keep the results in perspective, it is essential that the physical characteristics of the rider group be examined in order to identify those which have significant effects on stability. Thus, we are primarily interested in rider weight and stature. Data for this study were taken from a report of a study by Swearingen and Young for the Federal Aviation Agency entitled _Determination of Centers of Gravity of Children, Sitting and Standing_ (Reference C-1). This report covers children of both sexes in the age range of 5 to 18 years and provides data on weight, stature, sitting height, and c.g. location as well as many other measurements. For the purposes of the tricycle stability study, these data were reduced to mean values for the rider group under consideration. All computations are based on the values listed below.

Weight range : 30 to 60 lbs.

Vertical height of center-of-gravity above seat for a seated child (independant of weight) : 8 inches

Horizontal location of center-of-gravity in front of seat back for a seated child (independant of weight) : taken as acting directly above top of seat post (the reference gives a value of 5.2 inches)

Vertical height of center-of-gravity above floor for a standing child : 24 inches for 40 lbs. child. (57% of stature, taken as 42 inches)

Horizontal location of center-of-gravity in front of the plane of the back for a standing child : taken as acting directly above the rear axle (the reference gives a mean value of 2.8 inches)

The stability parameter derived in this analysis utilizes the location of the tricycle/rider center-of-gravity as a primary variable. This necessitates the measurement of weights and dimensions of the unit and their conversion to <u>computed</u> values for the two location terms, "a" and "h". The computations are made by treating the data in terms of a simple statics problem. Moments may be taken about the front wheel contact point to obtain the value of "a" and about the ground to obtain the value of "h". Using the symbols shown in Figure C-1, the equations for these terms are -

$$a = \frac{W_V\ a_1 + W_R\ a_2}{W_T}\ ;$$ the longitudinal location of the system c.g.

and $$h = \frac{W_V\ h_1 + W_R\ h_2}{W_T}\ ;$$ the vertical location of the system c.g.

where W_V = vehicle weight

W_R = rider weight

a_1 = distance to the vehicle center-of-gravity from the front wheel contact point

a_2 = distance to the rider center-of-gravity from the front wheel contact point

h_1 = height of the vehicle center-of-gravity above the ground

h_2 = height of the rider center-of-gravity above the ground

The dimension "b" (the distance from the rear wheel contact points forward to the system center-of-gravity) is simply the wheelbase (ℓ) minus the "a" dimension.

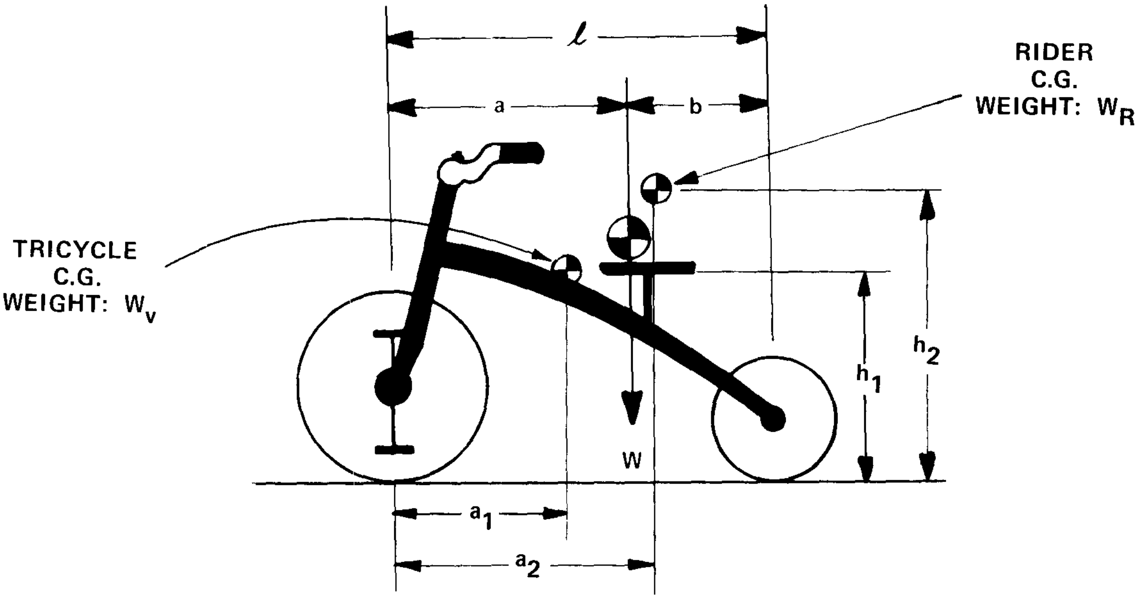


Figure C-1 CENTER-OF-GRAVITY LOCATION

The addition of a passenger on the rear axle step changes the values of both "a" and "h". If these modified terms are symbolized as "a_D" and "h_D", respectively, the previous equations can be converted for their evaluation. Thus,

$$a_D = \frac{a\ W_T + a_P\ W_P}{W_T + W_P}$$

and

$$h_D = \frac{h\ W_T + h_P\ W_P}{W_T + W_P}$$

where the subscript P denotes passenger characterisitics.