DOCUMENTATION OF INPUT FOR SINGLE VEHICLE ACCIDENT COMPUTER PROGRAM

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Evaluation of the Roadway Environment by
Dynamic Analysis of the Interaction Between
the Vehicle, Passenger, and Roadway

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FOREWORD

The information contained herein was developed on Research Project 2-5-69-140 entitled "Evaluation of the Roadside Environment by Dynamic Analysis of the Interaction Between the Vehicle, Passenger, and Roadway" which is a cooperative research study sponsored jointly by the Texas Highway Department and the U. S. Department of Transportation, Bureau of Public Roads.

Basically, the objectives of the study are to apply mathematical simulation techniques in determining the dynamic response of vehicles and their passengers when in collision with various roadside objects or when traversing curves in the road, shoulders, or other situations. It is a three-year study with a proposed completion date of August 1971.

As part of the first year's work, the Single Vehicle Accident computer program developed by Cornell Aeronautical Laboratory was adapted to the IBM 360 computer facilities at Texas A&M University. In so doing, the researchers familiarized themselves with the logic and coding of the program and wrote this document which describes its input data requirements. In adapting the program, additions and modifications were made which increased its flexibility and usefulness. These changes are also documented in this report.

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads.

ABSTRACT

Within the past few years, Cornell Aeronautical Laboratory has developed a digital computer program which determines the motions of a single vehicle that occur prior to and during departures from the roadway for given terrain and/or obstacle configurations. This program has been adapted to the computer facilities of both the Texas Transportation Institute at College Station and the Texas Highway Department at Austin. In adapting it, the researchers familiarized themselves with the logic and coding of the program and subsequently wrote this document which describes its input requirements and some of its typical uses. Additions and modifications were also made to the program, increasing its flexibility and usefulness, all of which are documented in this report.

This report is intended as a *supplement* to previously published reports by Cornell Aeronautical Laboratory, in particular the input data for the program. When used in this manner, it should considerably reduce the amount and complexity of work involved in implementing the program.

SUMMARY

During the first year's effort of this three-year study, the Single Vehicle Accident computer program, developed by Cornell Aeronautical Laboratory, was adapted to the IBM 360 computer facilities at Texas A&M University. To accomplish this and to take advantage of its many applications, it was necessary that the researchers delve into all phases of the program including its logic and coding. Considerable time was expended in determining the various input parameters required for specific situations.

As an aid to the researchers and the sponsor, this report, describing the program's input and its format, was written. All available quantitative input data are presented. Comments regarding some of the input parameters are included to help reduce the time needed for setting up the data and in some cases to reduce computer time.

In adapting the program, additions and modifications were made which increased its flexibility and usefulness. These changes are also documented in this report.

It is noted that this report is intended as a *supplement* to previously published reports by Cornell Aeronautical Laboratory on the Single Vehicle Accident computer program. When used in this manner, it should considerably reduce the work involved in implementing the program.

IMPLEMENTATION STATEMENT

Obviously, full implementation of this research effort cannot be expected until completion of the project, scheduled for August 1971. However, after the first year's work (1968-69), a part of which is documented in this report, some application of the research has begun, both directly and indirectly related to the Texas Highway Department.

Indirectly, the Single Vehicle Accident program is being used on other projects at the Texas Transportation Institute. One study is concerned with the effects that side and back slopes have on the motion of a vehicle that leaves the roadway. Another study is concerned with the feasibility of using earth berms to redirect out-of-control vehicles, in a manner similar to guardrails.

Directly, the Single Vehicle Accident program has been adapted to the computer facilities of the Texas Highway Department in Austin, thereby affording the Department a valuable tool that can be used to investigate various problems. Some of the problems that can be considered are the handling response of a vehicle during lane change maneuvers, the response of a vehicle traveling over arbitrary terrain configurations, skid response, vehicle spin-out on horizontal curves (with or without superelevation), and others. With the aid of this report and the pertinent reports published by Cornell Aeronautical Laboratory, it is a relatively simple matter to use the program.

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I. Introduction

To facilitate the design and evaluation of a roadway and its near environment, it is beneficial to know the effects that various design features have on the dynamic response of the vehicle and passenger. Roadway alignment of horizontal curves, superelevation, and ramps are determined, to a large degree, by the ability of a vehicle to negotiate these features. This ability is dependent upon the dynamic interaction between the vehicle and the roadway surface. Design of the roadway subgrade, pavement, and bridges is dependent upon static and dynamic loads imposed by vehicular traffic. From the safety aspect it is advantageous to know the effects of vehicle collisions with various roadside obstacles, such as guardrails, bridge rails, median barriers, sign posts, and others. In the areas adjacent to the traveled way it is important to know the effects that shoulders, side slopes, and back slopes have on a vehicle's motion.

It is felt that the problems mentioned above can be studied and evaluated satisfactorily with the use of mathematical simulation techniques. If these problems were studied using full-scale tests, the expense would likely be prohibitive and the number of variables that could be studied would be limited.

As an initial step in this study, a computer program (References 1 and 3), designated as CALSVA, was obtained from Cornell Aeronautical Laboratory and adapted to the computer facilities at Texas A&M University. Basically, the program determines the motions of a single vehicle that occur prior to and during departures from the roadway for given terrain and/or obstacle configurations.

To adapt the program and to take advantage of its many applications, a comprehensive study was made to determine its logic, coding, and input requirements. Considerable time was expended in determining various input parameters required for specific situations.

1.1 Purpose and Scope

As an aid to the researchers and the sponsor, this report, describing the program's input and its format, was written. All available quantitative input data are presented. Comments regarding some of the input parameters are included to help reduce the time needed for setting up the data and in some cases to reduce computer time.

In adapting the program, additions and modifications were made which increased its flexibility and usefulness. These changes are documented in this report.

It is noted that this report is intended as a *supplement* to published reports (References 1, 2, and 3) by Cornell Aeronautical Laboratory. The development of the computer program and the theory employed in its formulation is given in these referenced reports, and it was therefore not within the scope of this study to do so. When used in conjunction with the Cornell reports this document should considerably reduce the amount of work involved in implementing the program.

1.2 Additions and Modifications to Original Program

In adapting the CALSVA program the following additions and modifications were made.

a. To facilitate interpretation of the program's digital output, its plotting capabilities were completely revised. Significant parameters were made available to the CAL-COMP plotter routines for generation of two variable plots.

   As explained in Part 2.2 of this report, the user may obtain a total of 19 graphical plots while choosing from 19 selected variables, any two of which may be plotted against each other. For example, one of these 19 plots may be a so-called "XTRK vs. YTRK plot" (see Table 2-9) which is an X-Y plot of the path of each of the four wheels of the vehicle as they traverse the given terrain.

   The plots are 5" x 7" in size, contain adjusted scales for easy reading, and are identified by titles and/or figure numbers which the user specifies as input data.

b. A major addition to the program allows the vehicle-body to interact with the terrain or ground surface. Selected points on the vehicle body are entered as input and monitored for terrain contact. When contact occurs, forces normal and tangential to the terrain are applied to the vehicle at the point or points of contact.

   This vehicle-ground contact capability is important in instances where the vehicle's bumper or underside engage the terrain configuration or when determining the vehicle's motion during rollover. It is emphasized, however, that the formulation used in this feature is only a first order approximation based on the following assumptions.

(1) The vehicle structure remains undeformed.

(2) The terrain deforms and applies forces to the vehicle based on its stiffness and damping characteristics.

(3) Because of the complexity of the soil problem involved, the authors decided to allow only point contact between the soil and the vehicle. To obtain a value for soil stiffness, an estimated contact area of 100 in.^{2} is used. For example, if the soil under consideration has a subgrade modulus of "N" pounds per cubic inch then the soil stiffness becomes 100 x N pounds per inch. A discussion of this feature is given in Appendix D.

c. Input deck size has been minimized by adding a subroutine (entry STD to subroutine STAN) which generates data for a "typical vehicle" (a 1963 Ford Galaxie, four-door sedan, was chosen because it was used in the validation of the CALSVA program) by presetting required variables. This preset function is executed before each input data group is read, then required input data is read. This sequence of processing allows preset data to be changed if desired.

d. The terrain input procedure has been changed to a template input, which defines the terrain by a series of cross-sections. This is advantageous over the original "grid system" because terrain slopes are now computed by the program instead of being input by the user.

Also, as an added feature of the template input, it is now possible to generate a terrain containing varying surface-friction coefficients as a function of position (see 16th series of cards, Part 2.1).

e. Another added feature gives the user the following two options for specifying the initial position of the vehicle:

(1) the original method of inputting X'_{co}, Y'_{co}, Z'_{co}, ϕ_o, Θ_o and Ψ_o (see Appendix B2 for definitions); or

(2) inputting only X'_{co}, Y'_{co}, and Ψ_o and letting the program compute Z'_{co}, ϕ_o, and Θ_o such that the vehicle rests on the terrain.

1.3 General Input Requirements

All input data needed to complete one event, e.g., a vehicle striking a guardrail, is defined herein as a *data group*. As a matter of convenience, the data group is divided into two sections, the first necessary for computations and the latter deals with information necessary for CAL-COMP plot generations. Any number of data groups may be submitted together, and as such constitute a *computer run*.

Section 1. The first two cards of this section are title cards, and their contents will be printed at the top of each output page. Both cards must always be included in each data group. If the standard plot option (described in Part 2.2 of this report) is chosen, the contents of the first card are also printed out on each plot. The 3rd card, 16th series of cards, and the final card must always be included in each data group.

The remaining input cards in Section 1, needed for specific events, are described in Part 2.1 and Appendix B. Not all of this input is necessarily required for a given event. The user should refer to References 1, 2, and 3 for the input needed for a particular event.

As mentioned in Part 1.2, provisions have been made to reduce the amount of input data. The characteristics of a *typical* vehicle are available to the program (in Subroutine STAN) and will be used unless otherwise specified. Input supplied are the contents of cards 4 through 13 and card series 14, 17, and 23. If other data is required, the card or cards of this group which are appropriate and their ICARD number should be input. The ICARD number is used as an identification code by the program in storing the data.

In some cases recommended values are given in the report for certain variables. The value of these variables supplied by STAN are in agreement with the recommended values.

Note that the input is referred to by card number up through Card 13 and by series of cards thereafter. This is done since the exact number of input cards is variable after the first 13 and depends on the event simulated. Also, note that the format listed for the input parameters can and in many cases must be overridden.

Section 2. In addition to the digital output, three options are available to the user for plotting the output. One may choose a standard set of plots, a specified number of plots, or no plots. A description of the input requirements for each of these options is given in Part 2.2.

Termination Card. Part 2.3 of this report describes the input needed to terminate a computer run.

1.4 Typical Program Uses

The CALSVA program, at the state of development documented in this report, can be used to investigate the following situations:

(a) Handling response, i.e., observing the vehicle's response for lane change maneuvers or any such maneuver for which the steering angle (ψ_f) is known as a function of time (Part 2.1, 15th series of cards).

(b) Ride response, i.e., observing the vehicle's response while traveling over arbitrary terrain (roadway, ditches, ramps, side slopes, earth berms, etc.).

(c) Simultaneous handling and ride response which involves a combination of (a) and (b) above.

It is noted that the mathematical model has the capability of allowing the steering angle of the tires to be determined by the interactive forces between the tires and the terrain. The condition, called a *steer degree of freedom*, is used to simulate the case of a vehicle in which the driver has lost contact with the steering wheel, thus having no control over its direction. The steer degree of freedom is activated by setting INDCRB = 1.0 on the 3rd card (Part 2.1). TTI has used the steer degree of freedom in studies of side slopes and earth berms.

(d) Skid response, i.e., observing the vehicle's response during a skid.

A skid can be generated by a proper combination of steering angles and applied torques (Part 2.1, 15th series of cards).

(e) Curb impact, i.e., observing the vehicle's response during interaction with a curb or bridge rail (Part 2.1, 17th series of cards). During curb impact it is recommended that the more accurate tire model (the radial-spring tire model) be activated, which is accomplished by setting INDCRB = 1.0 on the third card of Part 2.1.

(f) Barrier impact, i.e., observing the vehicle's response during collision with a barrier.

Four types of barriers can be studied:

1) rigid barrier with a finite vertical dimension,
2) rigid barrier with an infinite vertical dimension,
3) deformable barrier with a finite vertical dimension,
4) deformable barrier with an infinite vertical dimension.

The input information for a vehicle-barrier collision is described in Part 1.2 of this report (20th, 21st, and 22nd series of cards).

These are just typical uses available to the roadway designer. Any combination of these could conceivably be used in an effort to simulate the designer's particular problem.

II. Input Description

2.1 Data Group - Section 1

1st and 2nd Cards (always included)

Format (18A4)

As stated above, these are title cards containing alphameric information in columns 1-72, for the purpose of identification.

3rd Card

Program Control Parameters (always included)

Format (9F8.0,I8)

Col. Nos.	Program Variable	*Report Variable	Definition	Units
1-8	T0		Start time of event	sec
9-16	T1		End time of event	sec
17-24	DTCOMP		Increment of integration	sec
25-32	DTCMP1		= 0.0, program computes initial position of vehicle to rest on terrain. = 1.0, user provides all initial vehicle position data.	
33-40	DTPRNT		Output interval	sec
41-48	THMAX		Value of THETA at which we shift planes usually = 70°	
49-56	UVWMIN		See comments	
57-64	PQRMIN		See comments	
65-72	INDCRB		See comments	

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*"Report" is taken to mean either this report or any of the CAL reports referenced herein.

3rd Card (Continued)

Col. Nos.	Program Variable	*Report Variable	Definition	Units
80	ICARD		= 1	

Comments on 3rd Card

TO - Usually 0.0, however, an event can start at any desired time.

DTCOMP - CAL uses 0.005-0.01 seconds depending on the character of the run. TTI has not used larger than 0.005; and runs made with 0.001 produced essentially the same results as with 0.005.

DTCMP1 - See comments for 10th and 11th cards.

DTPRNT - TTI prints the output every other increment of integration; for example, if DTCOMP = 0.005, DTPRNT = 0.01.

UVWMIN
&
PQRMIN - Absolute value of the resultant translational velocity (in./sec.) and angular velocity (deg./sec.), respectively, of the vehicle center of gravity at which the program will terminate computations. Both the translational velocity <u>and</u> the angular velocity of the vehicle must be equal to or less than these values before termination occurs. TTI uses 0.0 for both values.

INDCRB - Three values are used and their function is as follows:

(1) 0.0 - allows steering angles to be read in tabular form (15th series of cards); or, if not read in tabular form the initial steering angle (PSIFIO) of the 10th card is maintained throughout the computations, i.e., from the start to the end of the event.

(2) 1.0 - activates the steer degree of freedom and the radial tire model. In this case the curb input (17th series of cards) must be included.

(3) -1.0 - activates the steer degree of freedom only.

4th Card

Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-8	MODE		Mode of integration = 0.0 Variable Adams-Moulton = 1.0 Runge-Kutta = 2.0 Fixed Adams-Moulton	
9-16	EBAR		Applicable only if Mode = 0.0 See PINT1 Subroutine	
17-24	EM			
25-32	AAA			
33-40	HMAX			
41-48	HMIN			
49-72			blank	
80	ICARD		= 2	

Comment on 4th Card

MODE - TTI has used MODE = 1.0, exclusively (Runge-Kutta).

5th Card

Inertial Data

Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-8	XMS	M_S	See Appendix	Lb-Sec^2/In.
9-16	XMUF	M_{UF}	"	Lb-Sec^2/In.
17-24	XMUR	M_{UR}	"	Lb-Sec^2/In.
25-32	G	g	= 386.4	In/Sec^2
33-40	XIX	I_X	See Appendix	Lb-in.-sec^2
41-48	XIY	I_Y	"	Lb-in.-sec^2
49-56	XIZ	I_Z	"	Lb-in.-sec^2
57-64	XIXZ	I_{XZ}	"	Lb-in.-sec^2
65-72	XIR	I_R	"	Lb-in.-sec^2
80	ICARD		= 3	

Comment on 5th Card

Typical values of inertial data are shown in Table 2-1 (from reference 1).

TABLE 2-1. INERTIAL DATA

	Typical Standard Size Sedan	Typical 1958 Production Car**	1953 Buick*	1963 Ford Galaxie Four-door Sedan***
M_S	8.280-9.8450	10.2530	10.6720	10.8180
M_{UF}	0.540-0.5910	0.5000	0.7240	0.6080
M_{UR}	0.8860-0.9700	0.8070	1.1720	0.9450
I_X	4340.0-5160.0	6288.0	5592.0	6000.0
I_Y	23800.0-28300.0	30492.00	33600.0	30000.0
I_Z	25500.0-30320.0	36600.00	37068.0	36000.0
I_{XZ}	(-11.30)-(-13.40)	-14.500	-14.760	-192.0
I_R	613.00-670.00	508.00	733.00	600.0

* - See description on page 18, Fig. 3.2, Ref. 1

** - See description on page 27, Fig. 3.7, Ref. 1

*** - See reference 2 on page 64.

6th Card

Dimensions

Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-8	A	a	See Appendix	Inches
9-16	B	b	"	Inches
17-24	TF	T_F	"	Inches
25-32	TR	T_R	"	Inches
33-40	ZF	Z_F	"	Inches
41-48	ZR	Z_R	"	Inches
49-56	RHO	ρ	"	Inches
57-64	RW	R_W	"	Inches
65-72	AO	A_O	"	
80	ICARD		= 4	

Comments on 6th Card

1) A_0 = 4400.0 (recommended value, see reference 2)

2) Vehicle dimensions shown in Table 2-2 (from References 1 and 2)

TABLE 2-2. TYPICAL DIMENSIONS

	Typical Standard Size Sedan	Typical 1958 Production Car	1953 Buick	1963 Ford Galaxie Four-Door Sedan
a	51.600	50.04	62.610	54.517
b	66.400	67.44	62.890	64.483
T_F	60.300	58.80	59.000	61.0
T_R	59.300	58.80	62.200	60.0
Z_F	13.1845	10.8750	13.190	10.138
Z_R	15.0191	12.7030	15.520	12.088
ρ	-2.000	-2.000	-2.270	-2.00
R_W	14.000	13.500	14.40	15.00

7th Card

Suspension Data

Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-8	AKF	K_F	See appendix	Lb/In.
9-16	XLAMF	λ_F	"	
17-24	OMEGF	Ω_F	"	Inches
25-32	CF	C_F	"	Lb-Sec/In.
33-40	CFP	C'_F	"	Lbs.
41-48	EPSF	ε_F	"	In/Sec.
49-56	RF	R_F	"	Lb-In/Rad
57-64			Blank	
65-72			Blank	
80	ICARD		= 5	

Comments on 7th Card Shown in Table 2-3

TABLE 2-3. TYPICAL SUSPENSION DATA, PART 1

	Typical Standard Size Sedan	Typical 1958 Production Car	1953 Buick	1963 Ford Galaxie Four-Door Sedan
K_F	105.00	154.10	100.0	131.0
λ_F	6.0-25.0	3.00	3.00	25.0
Ω_F	2.5-4.0	3.50	3.00	3.00
C_F	5.0	6.80	4.00	3.5
C'_F	30.0	42.00	30.0	55.0
ε_F	0.001	0.001	0.001	0.001
R_F	98500.0	95800.0	106600.0	266000.0

8th Card

Suspension Data

Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-8	AKR	K_R	See Appendix	Lb/In.
9-16	XLAMR	λ_R	"	
17-24	OMEGR	Ω_R	"	Inches
25-32	CR	C_R	"	Lb-Sec/In.
33-40	CRP	C'_R	"	Lbs.
41-48	EPSR	ε_R	"	In/Sec.
49-56	RR	R_R	"	Lb-In/Rad
57-64	TS	T_S	"	Inches
65-72	AKRS	K_{RS}	"	
80	ICARD		= 6	

Comments on 8th Card Shown in Table 2-4

TABLE 2-4. TYPICAL SUSPENSION DATA, PART 2

	Typical Standard Size Sedan	Typical 1958 Production Car	1953 Buick	1963 Ford Galaxie Four-Door Sedan
K_R	110.0	106.25	110.00	192.0
λ_R	6.0-25.0	3.00	3.00	25.0
Ω_R	2.5-4.0	3.50	3.00	4.00
C_R	5.00	5.70	4.00	3.90
C'_R	18.00	4.000	18.00	50.0
ε_R	0.001	0.001	0.001	0.001
R_R	32500.0	23500.0	0.0	61900.0
T_S	45.0	38.28	50.00	46.5
K_{RS}	0.071	0.0	0.016	0.070

9th Card

Tire Data

Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-8	AKT	K_T	See Appendix	Lb/In.
9-16	SIGT	σ_T	"	Inches
17-24	XLAMT	λ_T	"	
25-32	A1	A_1	"	
33-40	A2	A_2	"	
41-48	A3	A_3	"	
49-56	AMU	μ	"	
57-64	OMEGT	Ω_T	"	
65-72	A4	A_4	"	
80	ICARD		= 7	

Comments on 9th Card

Recommended Values (from Ref. 2):

$K_T = 1098.0$
$\sigma_T = 3.00$
$\lambda_T = 10.00$
$A_1 = 8.276$
$A_2 = 2900.0$
$A_3 = 1.78$
$A_4 = 3900.0$
$\mu = 0.30$ to 0.80
$\Omega_T = 1.00$

10th Card

Initial Conditions (always included)

Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-8	PHIO	ϕ_o	See Appendix	Degrees
9-16	THETAO	θ_o	"	Degrees
17-24	PSIO	ψ_o	"	Degrees
25-32	PO	P_o	"	Deg/Sec
33-40	QO	Q_o	"	Deg/Sec
41-48	RO	R_o	"	Deg/Sec
49-56	PSIFIO	ψ_{Fo}	"	Degrees
57-64	PSIFDO	$\dot{\psi}_{Fo}$	"	Rad/Sec
65-72			Blank	
80	ICARD		= 8	

Comment on 10th Card

PHIO and THETAO are included only if DTCMP1 = 1.0 on 3rd card. If DTCMP1 = 0.0, PHIO and THETAO are left blank.

11th Card

Initial Conditions (always included)

Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable ,	Definition	Units
1-8	XCOP	X'_{co}	See Appendix	Inches

11th Card Continued

Col. Nos.	Program Variable	Report Variable	Definition	Units
9-16	YCOP	Y'_{co}	See Appendix	Inches
17-24	ZCOP	Z'_{co}	"	Inches
25-32	UO	U_o	"	In/Sec.
33-40	VO	V_o	"	In/Sec.
41-48	WO	W_o	"	In/Sec.
49-72			Blank	
80	ICARD		= 9	

Comments on 11th Card

1) ZCOP is included only if DTCMP1 = 1.0 on 3rd card. If DTCMP1 =0.0, ZCOP is left blank.

2) XCOP, YCOP, ZCOP, must never coincide to a template point, as described in 16th series of cards (Terrain Input).

12th Card

Initial Conditions

Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-8	DEL10	δ_{10}	See Appendix	Inches
9-16	DEL20	δ_{20}	"	Inches
17-24	DEL30	δ_{30}	"	Inches
25-32	PHILRO	ϕ_{RO}	"	Degrees
33-40	DEL10D	$\dot{\delta}_{10}$	"	In/Sec
41-48	DEL20D	$\dot{\delta}_{20}$	"	In/Sec
49-56	DEL30D	$\dot{\delta}_{30}$	"	In/Sec
57-64	PHIROD	$\dot{\phi}_{RO}$	"	Deg/Sec
65-72			Blank	
79-80	ICARD		= 10	

13th Card

Accelerometer Positions

Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-8	X1	X_1	See Appendix	Inches
9-16	Y1	Y_1	"	Inches
17-25	Z1	Z_1	"	Inches
26-32	X2	X_2	"	Inches
33-40	Y2	Y_2	"	Inches
41-48	Z2	Z_2	"	Inches
49-72			Blank	
79-80	ICARD		= 11	

Comment on 13th Card

This card is optional, however, its use is recommended. For the case where no accelerometer positions are being considered use (0,0,0) for the points (X_1,Y_1,Z_1) and (X_2,Y_2,Z_2).

14th Series of Cards

FRONT WHEEL CAMBER (ϕ_c) vs. SUSPENSION DEFLECTION (δ_f)

a. 1st card of series, Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-8	DELB		Initial Value for δ_f	Inches
9-16	DELE		Final Value for δ_f	Inches
17-25	DDEL		Increment for δ_f	Inches
26-78			Blank	
79-80	ICARD		= 12	

(DELE must be > DELB and [DELE - DELB/DDEL] $\leq$ 49.)

b. The second card and succeeding cards contain the PHIC (ϕ_c) Table (see reference 1). It consists of [DELE - DELB/DDEL] + 1 entries, 13 to a card (Format (13F6.3)). The units must be "degrees".

Comments on 14th Series

A typical set of values for ϕ_c vs. δ_f is shown in Table 2-5.

TABLE 2-5. TYPICAL ϕ_c vs. δ_f VALUES

δ_f(inches)	ϕ_c(degrees)
-5.00	-3.55
-4.00	-2.55
-3.00	-1.80
-2.00	-1.30
-1.00	-0.95
0.00	-0.55
1.00	-0.30
2.00	-0.30
3.00	-0.40
4.00	-0.55
5.00	-0.80

For this set of data, the 14th series of cards is as shown in Table 2-6.

TABLE 2-6. SAMPLE INPUT FOR 14th SERIES

1st Card

Col. Nos.	Information
1-8	-5.00
9-16	5.00
17-24	1.00
25-72	blank
79-80	12

2nd Card

Col. Nos.	Information
1-6	-3.55
7-12	-2.55
13-18	-1.80
19-24	-1.30
25-30	-0.95
31-36	-0.55
37-42	-0.30
43-48	-0.30
49-54	-0.40
55-60	-0.50
61-66	-0.80
67-72	blank
73-78	blank

Had there been more than 13 entries for ϕ_c, one or more additional cards similar to the 2nd card would have been required.

15th Series of Cards

Driver Control Inputs

a. 1st card of series, Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-8	TB		Initial Time for Driver Control Inputs	sec
9-16	TE		Final Time for Driver Control Inputs	sec
17-24	TINCR		Increment Time for Driver Control Inputs	sec
25-32	NTBL1		= 0.0, read ψ_f table = 1.0, do not read ψ_f table	
33-40	NTBL2		= 0.0, read TQ_F table = 1.0, do not read TQ_F table	
41-48	NTBL3		= 0.0, read TQ_R table = 1.0, do not read TQ_R table	
49-72			blank	
79-80	ICARD		= 13	

(TE must be > TB and [TE-TB/TINCR] $\leq$ 49)

b. The second card and succeeding cards contain tables of PSIF (ψ_f) TQF (TQ_F), and TQR (TQ_R), in that order, depending on the value of NTBL1, NTBL2, and NTBL3, respectively: For each variable with a 0.0 value there must follow a table with [TE-TB/TINCR] + 1 entries, 13 to a card (Format (13F6.3)) containing data relative to that variable. For each non-zero, the respective table is omitted.

Comments on 15th Series

If no steering inputs are required, i.e., the vehicle follows a straight line path into the target area, this series is not required.

The units are PSIF (degrees) and TQF and TQR (lb-ft). See the Appendix for definition of other terms.

16th Series of Cards

Terrain Input (always include)

a. 1st card of series, Format (9F8.0, I8)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-8	NBX		No. of templates along X' axis	
9-16	NBY		No. of points in Y' direction on each template	
17-24	NMUXY		No. of variable coefficient friction patches	
79-80	ICARD		= 14	

Comments for Card a.

This card gives the necessary information to describe the template to be used to input the terrain information. Each template <u>must have</u> NBY points. The templates are assumed to be normal to the X' axis. A maximum of 21 templates (NBX) and 21 points (NBY) per template may be used. The template information is entered on cards that immediately follow the first card of this series. If no terrain is to be input, set NBX = NBY = 0 and <u>do not</u> include template cards (this assumes flat level terrain with Z' = 0). NMUXY is the number of terrain patches which will have coefficients of friction different from AMU read in on the 9th card (ICARD = 7). There are a total of (NBX) x (NBY) patches with a maximum of 21 x 21 = 441.

b. Terrain **Template** Cards (include if NBX and NBY greater than 0)

The following cards will describe the template.

Format (I3,F7.0,(10F7.0))

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-3	ITEMP(I)		Template No. (i.e., 1,2,3...21)	
4-10	XTEMP(I)		X'g value of template ITEMP(I)	ft.
11-17	YGP(I,J)	Y'_g	Y'_g value of point J=1 on template ITEMP(I)	ft.
18-24	ZGP(I,J)	Z'_g	Z'_g value of point J=1 on template ITEMP(I)	ft.
25-31	YGP(I,J+1)	Y'_g	Y'_g value of point J=2 on template ITEMP(I)	ft.
32-38	ZGP(I,J+2)	Z'_g	Z'_g value of point J=2 on template ITEMP(I)	ft.

Continue with input of YGP's and ZGP's (10F7.0) through Column 80 and on successive cards until NBY points for template ITEMP(I) have been entered. On all continuation cards enter these values starting in col. 1 (there will be a maximum of four continuation cards per template). Start a new card for each template (part b is repeated for each template).

The following rules should be observed in developing a surface:

(1) the templates are always normal to the X' axis,

(2) the values of XTEMP(I), YGP(I,J) and ZGP(I,J) are referenced to the X', Y', Z' axis,

(3) points on each template are numbered consecutively,

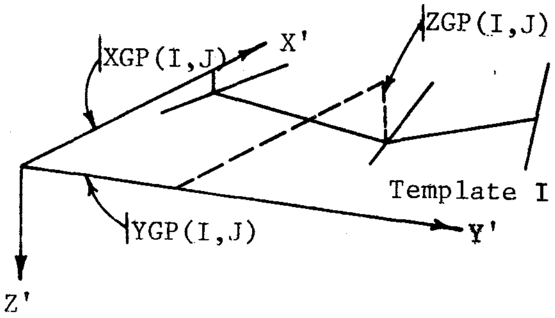

Figure 2-1. Template Coordinates

(4) The point YGP(I,1), ZGP(I,1) is always contained in the X'Z' plane.

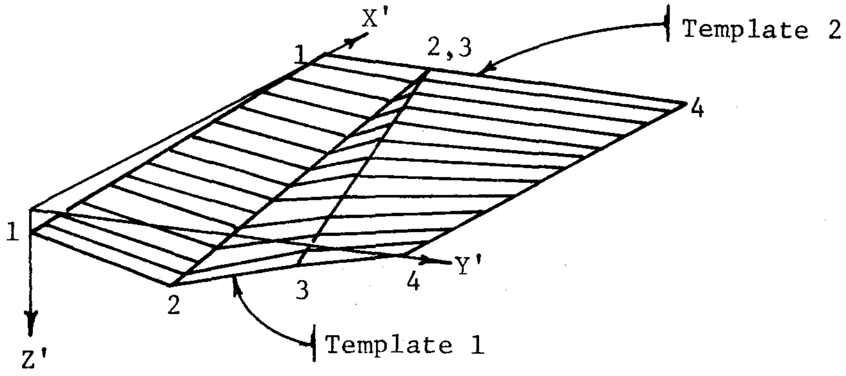

Figure 2-2. Converging Boundary Lines

Each template must have the same number of points. If two or more boundary lines converge, as in Figure 2-2, that point represents the ends of two lines (2 and 3) and YGP (2,2) = YGP(2,3) and ZGP(2,2) = ZGP(2,3).

(5) the area outside the limits described by the terrain template is assumed to be horizontal (plane X'Y') with Z' = 0.

c. Variable Coefficient of Friction Card (include if NMUXY > 0)

The following cards will describe the **terrain** patches over which it is desired to change the coefficient of friction. A terrain patch is defined as the surface enclosed between two templates (I, I+1) and two successive points (J, J+1) on the templates (I, I+1) (c.f. Figure 2-3).

Format (2I2,F6.0)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-2	I		Template No. (i.e., 1,2,3,...21)	
3-4	J			
5-10	AMUXY(I,J)		Friction Coeff. for Patch I,J	

Note: Use one card for each patch

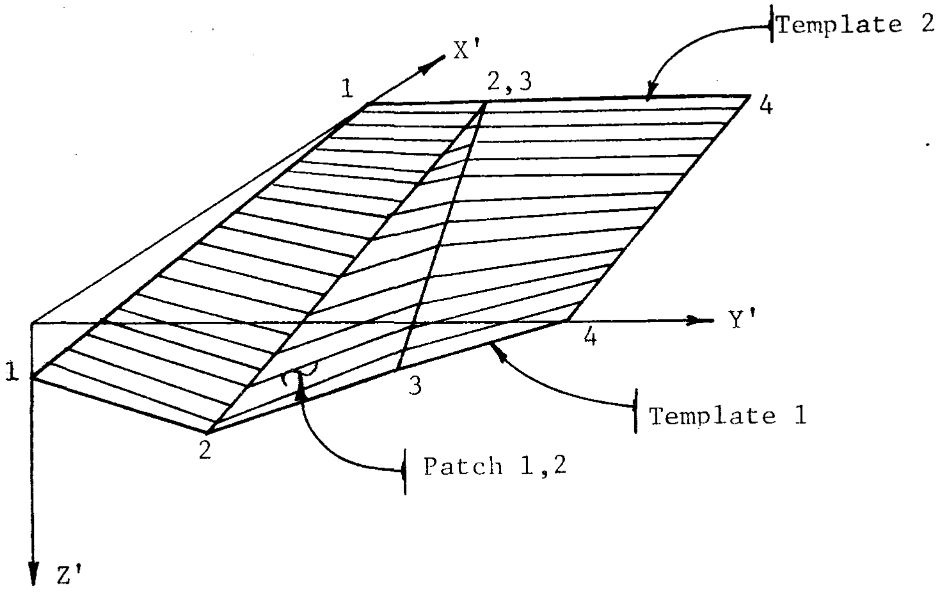

Figure 2-3. Friction Patches

Example: Change the coefficient of friction on the terrain patch bounded by templates 1 and 2 and lines 2-2, and 3-3 to AMUXY = 0.70.

Col. No.	1	2	3	4	5	6	7	8	9	10
	0	1	0	2			0	.	7	0

17th Series of Cards

Curb Input

One card, Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-8	YC1P	Y'_{c1}	See Appendix	Inches
9-16	YC2P	Y'_{c2}	"	Inches
17-24	ZC2P	Z'_{c2}	"	Inches
25-32	DELTC	$(\Delta t)_c$	Increment of Integration During Curb Impact	Seconds
33-40	PHIC1	ϕ_{c1}	See Appendix	Degrees
41-48	PHIC2	ϕ_{c2}	"	Degrees
49-56	AMUC	μ_c	"	
57-72			blank	
79-80	ICARD		= 15	

Comment on 17th Series

TTI uses DELTC = 0.001 seconds.

18th Series of Cards

Parameters Needed for Generating the FJP (F_j') Table

One card, Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable	*Definition	Units
1-8	RWHJB		Initial Value of R_W-h_j' for F_j' Table	Inches
9-16	RWHJE		Final Value of R_W-h_j' for F_j' Table	Inches
17-24	DRWHJ		Increment Value of R_W-h_j' for F_j' Table	
25-72			Blank	
79-80	ICARD		= 16	

*See Appendix for definitions

Comments on 18th Series

1) This series is included when INDCRB = 1.0 (curb impact)

2) The F_j' table is generated in subroutine "WHEEL".

3) ([RWHJE - RWHJB/DRWHJ] + 1) must be $\leq$ 35. Typical values are RWHJB = 0.0, RWHJE = 6.0,and DRWHJ = 0.25.

19th Series of Cards

Inertial Properties of Steering System

One card, Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-8	XIPS	I_ψ	See Appendix	Lb-Sec^2-In.
9-16	CPSP	C'_ψ	"	Lb-in.
17-24	OMGPS	Ω_ψ	"	Radians
25-32	AKPS	K_ψ	"	Lb-In/Rad
33-40	EPSPS	ε_ψ	"	Rad/Sec
41-48	XPS	$\overline{PT}$	"	Inches
49-72			Blank	
ICARD			= 17	

Comments on 19th Series

1) This card is included whenever the steer mode degree of freedom is to be activated (INDCRB = 1 or -1, third card).

2) Typical values (standard size sedan):

$I_\psi = 492.0$
$C'_\psi = 600.0$
$\Omega_\psi = 0.40$
$K_\psi = 5000.0$
$\varepsilon_\psi = 0.075$
$\overline{PT} = 1.50$

20th Series of Cards

Vehicle and Barrier Dimensions

One card, Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-8	YBPO	$(Y'_B)_o$	See Appendix	Inches
9-16	DELYBP	$\Delta Y'_B$	"	Inches
17-24	ZBTP	Z'_{BT}	"	Inches
25-32	ZBBP	Z'_{BB}	"	Inches
33-40	XVF	X_{VF}	"	Inches
41-48	XVR	X_{VR}	"	Inches
49-56	YV	Y_V	"	Inches
57-64	ZVT	Z_{VT}	"	Inches
65-72	ZVB	Z_{VB}	"	Inches
79-80	ICARD		= 18	

21st Series of Cards

Vehicle-Barrier Properties

One card, Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-8	AKV	K_V	See Appendix	Lb/In.^{3}
9-16	SET	$\overline{\text{SET}}$	"	
17-24	CONS	$\overline{\text{CONS}}$	"	
25-32	AMUB	μ_B	"	
33-40	EPSV	ε_V	"	In./Sec
41-48	EPSB	ε_B	"	Lb.
49-56	DELTB		Increment of Integration During Barrier Collision	Sec
57-64	INDB		= 1.0 Rigid Barrier Finite Vertical Dim. = 2.0 Rigid Barrier Infinite Vertical Dim. = 3.0 Deformable Barrier Finite Vertical Dim. = 4.0 Deformable Barrier Infinite Vertical Dim.	
65-72			Blank	
79-80	ICARD		= 19	

Comment on 21st Series

Typical Values:

$K_V = 4.0$

$\overline{\text{SET}} = 0.122$ (deformable barrier)

$\overline{\text{CONS}} = 0.56$ (deformable barrier)

$\mu_B = 0.2$

$\varepsilon_V = 1.0$

$\varepsilon_B = 500.0$

DELTB = 0.002 (used by TTI)

22nd Series of Cards

2 cards, Format (9F8.0)

These two cards contain 11 values of σ_R; 9 on the first card and 2 on the second with 8 columns per entry. ICARD = 20, and is punched in columns 79-80 of the first card.

See Appendix B1 for details.

23rd Series of Cards

Vehicle Monitor and Terrain Contact

a. 1st Card of Series, Format (9F8.0,I8)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-8	NVP		See Appendix	-----
9-16	SSTIFF		"	lb/in.
17-24	XJ		"	sec./in.
25-32	FRFAC		"	-----
79-80	ICARD		= 23	-----

Note: NVP cannot be greater than 28

b. 2nd card (to be used if NVP > 0.0) Format (12F6.0)

Col. Nos.	Program Variable	Report Variable	Definition	Units
1-6	XVP(I)*	x_{vp}.	See Appendix	in.
7-12	YVP(I)	y_{vp}.	"	in.
13-18	ZVP(I)	z_{vp}.	"	in.

*I = 1, NVP

Continue with same format on succeeding cards, twelve entrys (four points) per card, six columns per entry (Format (12F6.0)). The maximum number of cards of this type is seven.

Comments on 23rd Series of Cards

1) NVP (number of vehicle points to be monitored) is to be punched as a floating point number, i.e., if 10 points are desired then NVP is punched as 10.0.

2) Subroutine STAN presets only four vehicle monitor points to represent the four lower corners of the vehicle (four bumper points). In vehicle-fixed coordinates, for the 1963 Ford, TTI has decided to use the coordinate values shown in Table 2.7 for bumper points.

TABLE 2-7. BUMPER POINTS IN VEHICLE COORDINATES (INCHES)

I	XVP(I)	YVP(I)	ZVP(I)
1	81.517	39.5	12.138
2	81.517	-39.5	12.138
3	-117.483	39.0	8.138
4	-117.483	-39.0	8.138

Hence the user omits the 23rd Series of cards unless he wishes to monitor more points or different points than those shown in Table 2-7. By including the 23rd series, the preset values are overridden.

3) See Appendix B1 for more vehicle dimensions (Figures B1-3 and B1-4).

4) The following values are also preset by subroutine STAN:

NVP = 4.0

SSTIFF = 4.000

XJ = 0.001

FRFAC = 0.25

Comments on 23rd Series Continued

SSTIFF = 4000., is based on a soil subgrade modulus of 40 lb/in.^{3} and a contact area of 100 in.^{2} These preset values of SSTIFF, XJ, and FRFAC are not necessarily recommended values since these change for any given soil.

Final Card of Section 1

(always included)

Col. Nos.	Information
1-76	blank
77-80	9999

Note: This card signifies the end of data in Section 1

2.2 Data Group - Section 2

Three options are available for use in displaying the output generated by the CALSVA program. The CAL-COMP plot routines are utilized for this purpose. A brief description of each option follows.

1) option 1 - A group of 19 plots will be generated under this option. Table 2-8 lists the plots which are printed. Two types of identification are printed on each plot. The first is a Figure number which corresponds to those given in Table 2-8. The second is the contents of the first card of Section 1.
2) option 2 - Any number of plots, up to a total of 19, may be generated by choosing this option. Table 2-9 lists the variables available for plotting. The type of identification appearing in the plots is to be inputted according to subsequent instructions.
3) option 3 - If no plots are needed, this option is used.

For a given data group only one of these options may be selected. If another data group is submitted in the computer run, follow the cards required for the chosen plot option by the first card of Section 1 of the next data group, etc.

Description of each option input follows.

Option 1 - Standard Plots. One card required. Format (A4).

Col. No.	Information
1-4	STAN

Option 2 - N Plots. Three series of input cards are needed in this option; (a), (b), and (c).

(a) Plot Control Cards

Format (2A4)

TABLE 2-8. STANDARD PLOTS

Figure	Description*
1	XTRK versus YTRK
2	XPOS " AVER
3	YPOS " ZPOS
4	YPOS " AVER
5	YPOS " ALON
6	YPOS " ALAT
7	TIME " XPOS
8	TIME " YPOS
9	TIME " ZPOS
10	TIME " ALON
11	TIME " ACX2
12	TIME " ALAT
13	TIME " ACY2
14	TIME " AVER
15	TIME " ACZ2
16	TIME " ROLL
17	TIME " PTCH
18	TIME " YAWW
19	TIME " SANG

*See Table 2-9

TABLE 2-9. ALPHAMERIC VARIABLE NAMES

SEQUENCE NO.	NAME	PROGRAM VARIABLE	DESCRIPTION	PLOT UNITS
1	TIME	TM	Time in seconds	
2	XPOS	XPO	X, Y and Z coordinate, respectively, of sprung mass relative to space-fixed coordinate system	inches
3	YPOS	YPO		"
4	ZPOS	ZPO		"
5	ALON	ACLON	Sprung Mass Longitudinal Acceleration	G-units
6	ALAT	ACLAT	" " Lateral "	"
7	AVER	ACVER	" " Vertical "	"
8	ROLL	PHIO	Roll, pitch, yaw angles, respectively of vehicle	degrees
9	PTCH	THTAO		"
10	YAWW	PSIO		"
11	ACX1	AX1	Acceleration components in X, Y, and Z directions, respectively, at accelerometer position No. 1, relative to vehicle-fixed coordinate system	G-units
12	ACY1	AY1		"
13	ACZ1	AZ1		"
14	ACX2	AX2	Acceleration components in X, Y, and Z directions, respectively, at accelerometer position No. 2, relative to vehicle-fixed coordinate system	G-units
15	ACY2	AY2		"
16	ACZ2	AZ2		"
17	VDFO	DEFO	Vehicle deformation	inches
18	BDFL	DELBO	Barrier deflection	inches
19	SANG	PSIFO	Steering angle	degrees
20	XTRK	XTRK	X-position of vehicle wheel centers	inches
21	YTRK	YTRK	Y-position of vehicle wheel centers	inches

Col. Nos.	Variable Name to be Punched	Program Variable	Definition
1-4	*	See Table 2-9	Y (abcissa)
5-8	**	"	X (ordinate)

*Time is usually specified as the first variable, however, it can be any variable in the NAME column of Table 2-9. The variable to be entered here must have a sequence number less than the variable to be entered in cols. 5-8.

**Any other desired variable in the NAME column from Table 2-9. The sequence number of this variable must be greater than the sequence number of the variable in cols. 1-4.

NOTE:

1) One card is needed per plot. A maximum of 19 plots can be generated for each data group.

2) XTRK YTRK can only be plotted against each other.

(b) XXXX Card

Format (A4)

Col. No.	Information	Definition
1-4	XXXX	Signifies end of plot control cards

(c) Plot Identification Cards

Format (20A4)

Col. No.	Identification to be Punched
1-70	(whatever desired)

NOTE:

1) Two plot identification cards are required for each plot control card of series (a) and their order of input must follow that of the plot control cards. For example, if 10 plots are specified, 20 plot identification cards are required.

2) The information on each of these two cards is printed below each respective plot.

Option 3 - One card required.

Format (A4)

Col. No.	Information
1-4	NONE

2.3 Run Termination Card

In order to signify the end of a computer run a termination card must always be included. Its contents are as follows:

Format (A4)

Col. No.	Information
1-4	FINI

REFERENCES

1) McHenry, R. R., Segal, D. J., "Determination of Physical Criteria for Roadside Energy Conversion Systems," CAL No. VJ-2251-V-1, July 1967.

2) McHenry, R. R., "An Analysis of the Dynamics of Automobiles During Simultaneous Cornering and Ride Motions," Institution of Mechanical Engineers Symposium, "Handling of Vehicles Under Emergency Conditions," 8 January, 1969.

3) McHenry, R. R., and Deleys, N. J., "Vehicle Dynamics in Single Vehicle Accidents: Validation and Extensions of a Computer Simulation", CAL No. VJ-2251-V-3, December, 1968.

APPENDIX A

Appendix A - General Abbreviations

CAL - Cornell Aeronautical Laboratory

CAL-COMP - California Computer Products, Inc.

CALSVA - Cornell Aeronautical Laboratory Single Vehicle Accident

TTI - Texas Transportation Institute

APPENDIX B

Appendix B1 - Definitions of Input Parameters, Listed According to Number of Card Series

5th Card

M_S = sprung mass, lb-sec^2/in.

M_{UF} = front unsprung mass (both sides), lb-sec^2/in. ($M_1 = M_2 = M_{UF}/2$)

M_1, M_2 = front unsprung mass at a single wheel

M_{UR} = rear unsprung mass, lb-sec^2/in.

I_X, I_Y, I_Z, I_{XZ} = moments and product of inertia of sprung mass, lb-sec^2/in.

I_R = rear unsprung mass moment of inertia about a line through its center of gravity and parallel to the X axis, lb-sec^2/in.

6th Card

a = distance along the vehicle-fixed X axis from the sprung mass center of gravity to the centerline of the front wheels, inches

b = distance along the vehicle-fixed X axis from the sprung mass center of gravity to the centerline of the rear wheels, inches

T_F, T_R = tread at front and rear suspensions, respectively, inches

Z_F = static distance along the Z axis between the center of gravity (C.G.) of the sprung mass and the C.G. of the front unsprung masses (C.G. of the individual front masses assumed to coincide with the wheel centers), inches

Z_R = static distance along the Z axis between the C.G. of the sprung mass and the roll center of the rear axle, inches

ρ = distance between center of gravity of rear axle and rear axle roll center, positive for roll center above C.G., inches

R_W = undeflected radius of wheels, inches

A_0, A_1, A_2, A_3, A_4 = coefficients in the functional relationships fitted to tire side-force data (see Ref. 2)

7th and 8th Cards

K_F, K_R = suspension load - deflection rate for a single wheel, effective at the wheel in the quasi-linear range about the design position, for front and rear suspensions, respectively, lb/in.

λ_F, λ_R = multiples of K_F, K_R, respectively for use in suspension deflection stops (see Figure 4.6, Ref. 1).

Ω_F, Ω_R = maximum suspension deflections, from the position of static equilibrium relative to the vehicle, for quasi-linear load-deflection characteristics of the springs (see Figure 4.6, Ref. 1), inches.

C_F, C_R = viscous damping coefficient for a single wheel, effective at the wheel, for front and rear suspensions, respectively, lb-sec/in.

C'_F, C'_R = Coulomb damping for a single wheel, effective at the wheel, for front and rear suspensions, respectively, lbs.

$\varepsilon_F, \varepsilon_R$ = friction lag in front and rear suspensions, respectively, to prevent extraneous oscillations induced by round-off error in suspension velocities, in./sec.

R_F, R_R = auxiliary roll stiffness (i.e., roll stiffness in excess of that corresponding to the wheel rates in ride motions) at the front and rear suspensions, respectively, lb-in./radian.

T_S = distance between spring connections for solid rear axle, inches.

K_{RS} = rear axle roll-steer coefficient (positive for roll under-steer).

9th Card

K_T = radial tire rate in quasi-linear range for a single tire, lb/in.

σ_T = maximum radial tire deflection for quasi-linear load-deflection characteristic (see Figure 4.9, Ref. 1), inches.

λ_T = multiple of K_T for use in nonlinear range (i.e., travel limit) (see Figure 4.9, Ref. 1).

A_0, A_1, A_2, A_3, A_4 = coefficients in the functional relationships fitted to tire side-force data (see Ref. 2)

μ = tire-to-ground friction coefficient. This is the basic ground surface coefficient of friction.

Ω_T = decimal portion of A_2 at which the assumed parabolic variation of side force with tire loading is abandoned to preclude reversal in the sign of the side load under conditions of excessive tire loading (see Figure 4.13, Ref. 1)

10th Card

ϕ_o, θ_o, ψ_o = initial values of ϕ,θ,ψ (Euler angular coordinates of sprung mass relative to space-fixed system, degrees).

P_o, Q_o, R_o = initial values of P, Q, R (scalar components of sprung mass angular velocity, taken along X, Y, Z axes, respectively, degrees/sec. See page 111, Ref. 1.).

ψ_{FO} = initial value of ψ_F (steer angle of front wheels relative to vehicle coordinate axes system, positive for CW steer as viewed from above vehicle, degrees).

$\dot{\psi}_{FO}$ = initial value of steering angular velocity, radians/sec, (first time derivative of ψ_F).

11th Card

X'_{co}, Y'_{co}, Z'_{co} = initial values of X'_c, Y'_c, Z'_c (coordinates of the spring mass center of gravity relative to the space-fixed coordinate axes system, inches).

U_o, V_o, W_o = initial values of U, V, W (scalar components of linear velocity of spring mass, taken along X, Y, Z axes, respectively, inches/sec).

12th Card

δ_{10}, δ_{20}, δ_{30} = initial values of δ_1, δ_2, δ_3 (suspension deflections relative to the vehicle from the positions of static equilibrium, at the right front wheel center, left front wheel center, and rear axle roll center, respectively, inches). See Ref. 1, page 111.

ϕ_{RO} = initial value of ϕ_R (angular displacement of the rear axle relative to the vehicle about a line parallel to the X-axis through the rear axle roll center, positive when clockwise viewed from rear, degrees). See page 111, Ref. 1.

$\dot{\delta}_{10}$, $\dot{\delta}_{20}$, $\dot{\delta}_{30}$ = initial values of suspension velocities (first time derivatives of δ_1, δ_2, δ_3, respectively). See page 111, Ref. 1.

$\dot{\phi}_{RO}$ = initial value of angular velocity of rear axle (first time derivative of ϕ_R, see page 111, Ref. 1).

13th Card

$\left.\begin{matrix} X_1, Y_1, Z_1 \\ X_2, Y_2, Z_2 \end{matrix}\right\}$ = coordinates of accelerometer positions on the sprung mass, at which acceleration components are to be calculated and printed out, inches. (with reference to the vehicle fixed axes)

15th Series of Cards

ψ_f = steer angle of front wheels relative to vehicle coordinate axes system, positive for CW steer as viewed from above vehicle, degrees.

TQ_F, TQ_R = applied torque for a single wheel, effective at the wheel, for front and rear wheels, respectively (positive for traction, negative for braking), lb-ft.

17th Series of Cards

See page 117, Ref. 1 for illustration of the following definitions:

Y'_{c1} = initial boundary of curb to be encountered by vehicle, inches (first slope change).

Y'_{c2} = boundary of second slope of curb, inches.

Z'_{c2} = elevation of curb profile at Y'_{c2}.

ϕ_{c1}, ϕ_{c2} = first and second curb slopes encountered by the vehicle, radians.

μ_c = tire-to-curb friction coefficient.

18th Series of Cards

R_W = undeflected radius of wheels, inches

h'_j = rolling radius of wheel j, inches

F'_j = the forces exerted by the individual radial springs when curb impact occurs. The spring model is shown diagrammatically in Figure 4.8, page 121, of the CAL Report VJ-2251-V-1 and the computation employing F'_j is on page 193 of the same reference. F'_j is derived from the radial load-deflection characteristics of the tires on flat terrain which is shown in the graph on page 122.

19th Series of Cards

I_{ψ} = moment of inertia of steering system, effective at front wheels (both sides included), 16-sec^{2}-in

C'_{ψ} = Coulomb resistance in steering system, effective at the wheels (both sides included), lb-in

Ω_{ψ} = angular deflection of the steering system at which elastic stops are encountered, radians

K_{ψ} = Load-deflection of the elastic stops in the steering system, effective at the wheels (both sides included), lb-in/rad

ε_{ψ} = friction lag in steering system, rad/sec

$\overline{PT}$ = pneumatic trail of front tires, inches

20th Series of Cards

Vehicle Dimensions for Barrier Impact

Note that for coordinate system shown in Figure B1-1, Z_{VT} X_{VR} are negative.

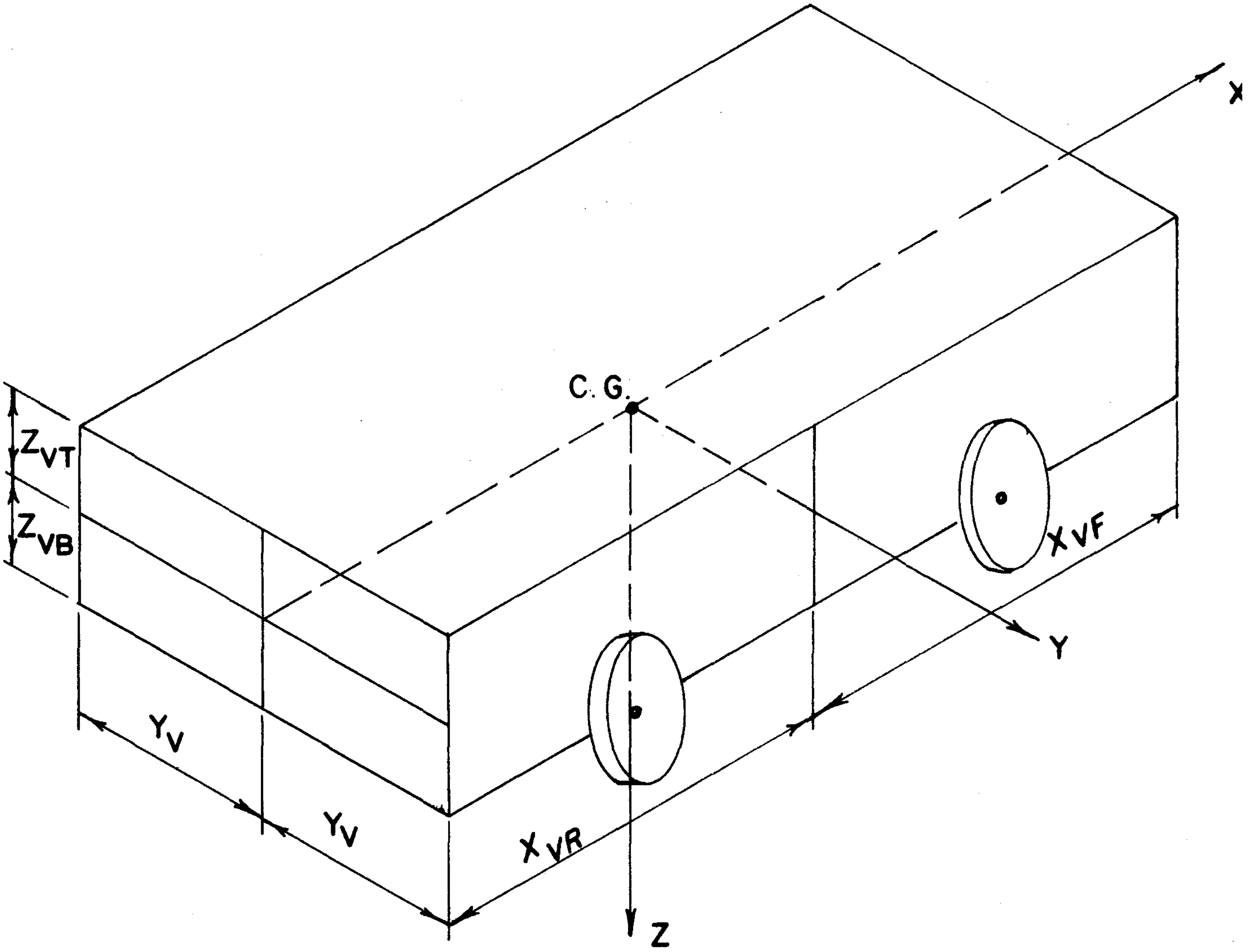

Figure B1-1
Vehicle Dimensions for Barrier Impact

20th Series of Cards (continued)

Barrier dimensions and position relative to space-fixed coordinate system

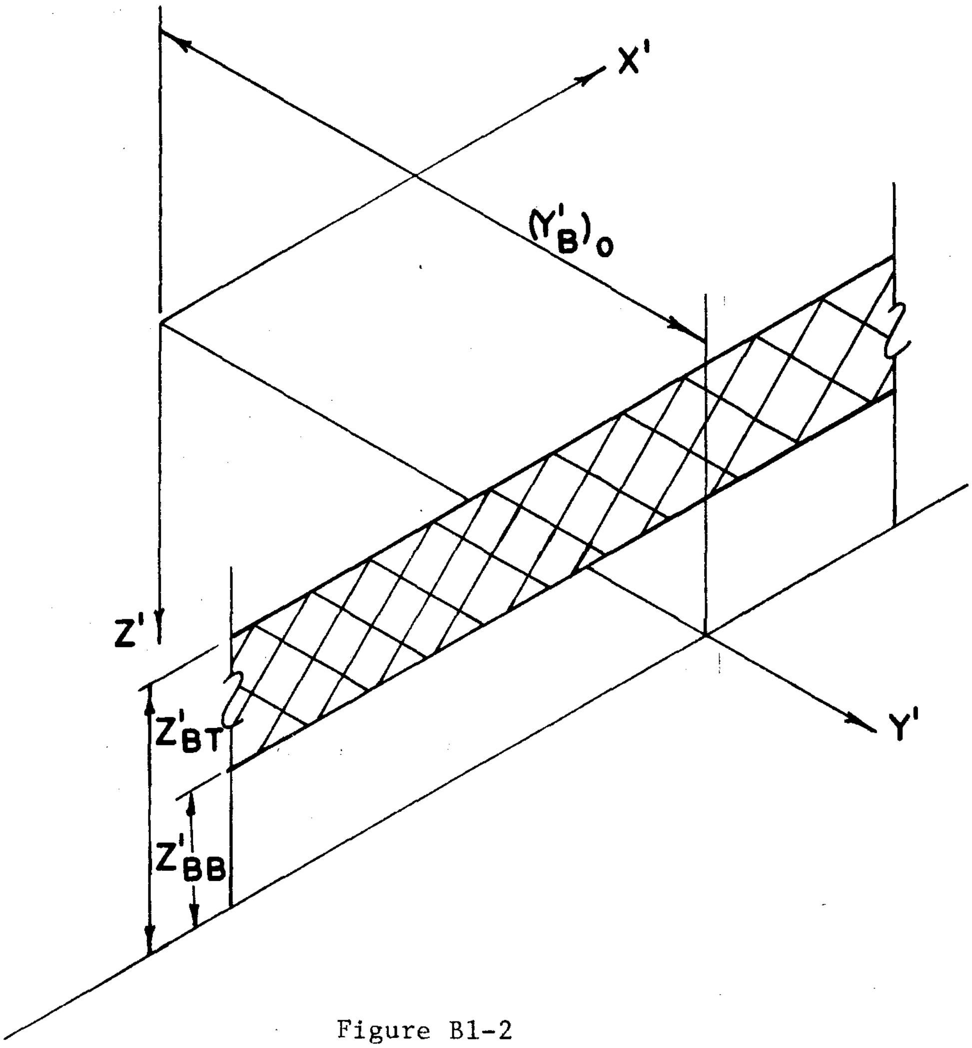

Figure B1-2
Barrier Dimensions and Position

As shown in Figure B1-2, the plane containing the barrier (cross-hatched) and the X'-Z' plane are parallel and separated by a distance of $(Y'_B)_0$. The bottom of the barrier is located at a distance of Z'_{BB} above the X'-Y' plane. The elevation of the top of the barrier relative to the X'-Y' plane is Z'_{BT}. It should be noted that for the coordinate system shown, both Z'_{BB} and Z'_{BT} are negative.

$\Delta Y'_B$ = size of incrementing step in establishing force balance between vehicle and barrier. (CAL uses 0.5 inches in ref 1. page 49)

21st Series of Cards

K_V = load-deflection characteristic of vehicle structure, lb/in^3

$\overline{SET}$ = ratio of permanent deflection to maximum deflection of barrier

$\overline{CONS}$ = ratio of conserved energy to maximum energy absorbed by barrier

μ_B = sprung mass-to-barrier friction coefficient

ε_V = friction lag in vehicle-to-barrier friction force, in/sec

ε_B = acceptable error in force balance between vehicle structure and barrier, lbs.

22nd Series

These first six coefficients define the barrier force-deflection curve in the form of a fifth degree polynomial.

$$F = \sigma_{R0} + \sigma_{R1}\delta + \sigma_{R2}\delta^2 + \sigma_{R3}\delta^3 + \sigma_{R4}\delta^4 + \sigma_{R5}\delta^5$$

The last 5 coefficients define a barrier force versus deflection velocity curve in the form of a fifth order polynomial.

$$F' = \sigma_{R6}\dot{\delta} + \sigma_{R7}\dot{\delta}^2 + \sigma_{R8}\dot{\delta}^3 + \sigma_{R9}\dot{\delta}^4 + \sigma_{R10}\dot{\delta}^5$$

The total force is meant to be

$$F_B = F + F'$$

However for the present simulation F' = 0 and the last five coefficients are zero.

23rd Series of Cards

NVP = number of points on the vehicle which are to be monitored for contact with the ground surface. These points also are the points on the vehicle to which the soil restoring forces are applied if contact is made with the ground surface.

SSTIFF = stiffness of ground surface, (lb/in.)

XJ = soil damping constant, (sec./in.)

FRFAC = coefficient of friction between vehicle and terrain

$\left.\begin{array}{l}\mathrm{XVP(I)}\\ \mathrm{YVP(I)}\\ \mathrm{ZVP(I)}\end{array}\right\}$ = coordinates of points on vehicle which are to be monitored referenced to the vehicle fixed axes. There can be a maximum of twenty-eight points. (coordinates in inches)

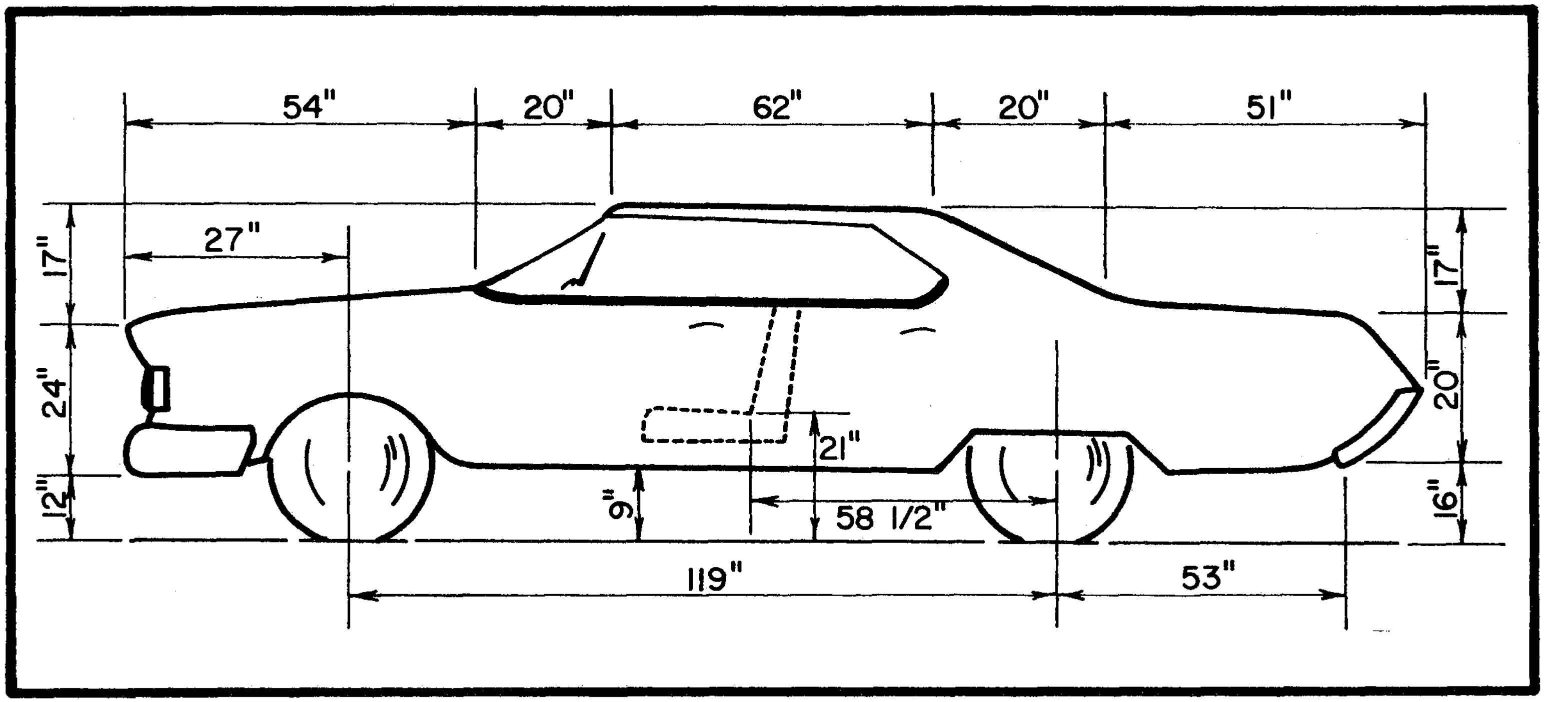

Figure B1-3. Approximate Body-Dimensions of the 1963 Ford, Part I

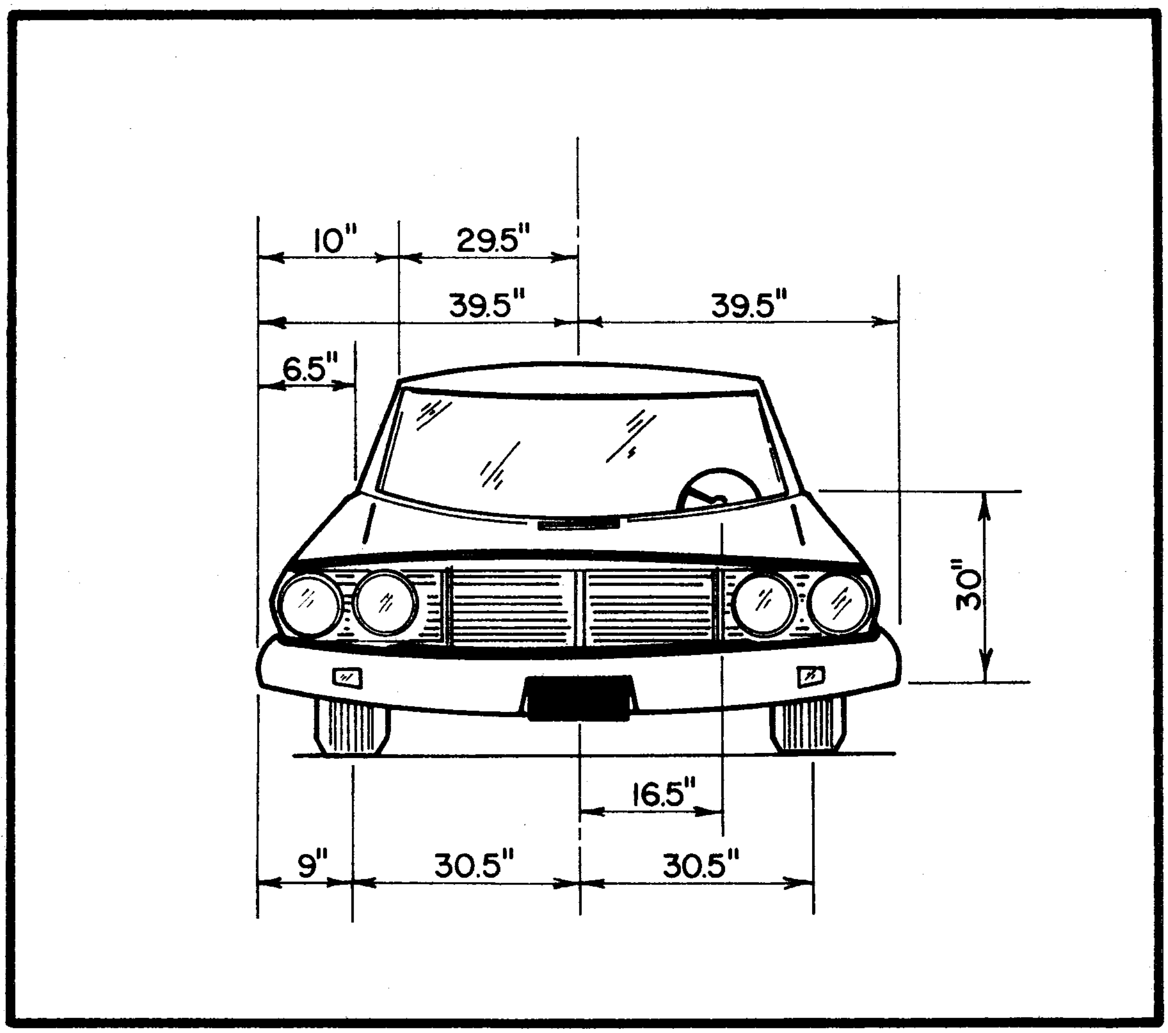

Figure B1-4. Approximate Body Dimensions of the 1963 Ford, Part II

APPENDIX B2 - DEFINITIONS OF INPUT PARAMETERS, LISTED ALPHABETICALLY

DESCRIPTION	ICARD
A=DISTANCE ALONG THE VEHICLE-FIXED X-AXIS FROM THE SPRUNG MASS CENTER OF GRAVITY TO THE CENTERLINE OF THE FRONT WHEELS	4
AAA=APPLICABLE ONLY IF MODE = 0, SEE PINT1 ROUTINE	2
AKF=SUSPENSION LOAD-DEFLECTION RATE FOR A SINGLE WHEEL, EFFECTIVE AT THE WHEEL IN THE QUASI-LINEAR RANGE ABOUT THE DESIGN POSITION FOR FRONT SUSPENSION	5
AKPS=LOAD-DEFLECTION OF THE ELASTIC STOPS IN THE STEERING SYSTEM, EFFECTIVE AT THE WHEELS (BOTH SIDES INCLUDED)	17
AKRS=REAR AXLE ROLL-STEER COEFFICIENT	6
AKR=SUSPENSION LOAD-DEFLECTION RATE FOR A SINGLE WHEEL, EFFECTIVE AT THE WHEEL IN THE QUASI-LINEAR RANGE ABOUT THE DESIGN POSITION FOR REAR SUSPENSION	6
AKT=RADIAL TIRE RATE IN QUASI-LINEAR RANGE FOR A SINGLE CARD	7
AKV=LOAD-DEFLECTION CHARACTERISTIC OF VEHICLE STRUCTURE	19
AMU=TIRE-TO-GROUND FRICTION COEFFICIENT	7
AMUB=SPRUNG MASS-TO-BARRIER FRICTION COEFFICIENT	19
AMUC=TIRE-TO-CURB FRICTION COEFFICIENT	15
AMUXY=FRICTION COEFFICIENT FOR A PARTICULAR FRICTION PATCH	14
A0=COEFFICIENT IN THE FUNCTIONAL RELATIONSHIPS FITTED TO TIRE SIDE FORCE DATA	7
A1=COEFFICIENT IN THE FUNCTIONAL RELATIONSHIPS FITTED TO TIRE SIDE FORCE DATA	7
A2=COEFFICIENT IN THE FUNCTIONAL RELATIONSHIPS FITTED TO TIRE SIDE FORCE DATA	7
A3=COEFFICIENT IN THE FUNCTIONAL RELATIONSHIPS FITTED TO TIRE SIDE FORCE DATA	7
A4=COEFFICIENT IN THE FUNCTIONAL RELATIONSHIPS FITTED TO TIRE SIDE FORCE DATA	7
B=DISTANCE ALONG THE VEHICLE-FIXED X-AXIS FROM THE SPRUNG MASS CENTER OF	

```
       GRAVITY TO THE CENTERLINE OF THE REAR WHEELS                        4
   BET=APPLICABLE ONLY IF MODE = 0, SEE PINT1 ROUTINE                      2
    CF=VISCOUS DAMPING COEFFICIENT FOR A SINGLE WHEEL, EFFECTIVE AT THE WHEEL,
       FOR FRONT SUSPENSION
   CFP=COULOMB DAMPING FOR A SINGLE WHEEL, EFFECTIVE AT THE WHEEL, FOR FRONT
       SUSPENSION                                                          5
  CONS=RATIO OF CONSERVED ENERGY TO MAXIMUM ENERGY ABSORBED BY BARRIER    19
  CPSP=COULOMB RESISTANCE IN STEERING SYSTEM, EFFECTIVE AT THE WHEELS,
       (BOTH SIDES INCLUDED)                                              17
    CR=VISCOUS DAMPING COEFFICIENT FOR A SINGLE WHEEL, EFFECTIVE AT THE WHEEL,
       FOR REAR SUSPENSION                                                 6
   CRP=COULOMB DAMPING FOR A SINGLE WHEEL, EFFECTIVE AT THE WHEEL, FOR REAR
       SUSPENSION                                                          6
  DDEL=INCREMENT FOR DELTA(F)                                             12
  DELB=INITIAL VALUE FOR DELTA(F)                                         12
  DELE=FINAL VALUE FOR DELTA(F)                                           12
 DELTB=INCREMENT OF INTEGRATION DURING BARRIER COLLISION                  19
 DELTC=INCREMENT OF INTEGRATION DURING CURB IMPACT                        15
DELYBP=SIZE OF INCREMENTING STEP IN ESTABLISHING FORCE BALANCE BETWEEN
       VEHICLE AND BARRIER                                                18
 DEL10=INITIAL VALUE OF DELTA(1) (SUSPENSION DEFLECTION  RELATIVE TO THE
       VEHICLE FROM THE POSITION OF STATIC EQUILIBRIUM AT THE RIGHT FRONT
       WHEEL CENTER)                                                      10
DEL10D=INITIAL VALUE OF SUSPENSION VELOCITY (FIRST TIME DERIVATIVE OF DELTA(1)10
 DEL20=INITIAL VALUE OF DELTA(2) (SUSPENSION DEFLECTION RELATIVE TO THE
       VEHICLE FROM THE POSITION OF STATIC EQUILIBRIUM AT THE LEFT FRONT
       WHEEL CENTER)                                                      10
DEL20D=INITIAL VALUE OF SUSPENSION VELOCITY (FIRST TIME DERIVATIVE OF DELTA(2)10
 DEL30=INITIAL VALUE OF DELTA(3) (SUSPENSION DEFLECTION RELATIVE TO THE
       VEHICLE FROM THE POSITION OF STATIC EQUILIBRIUM AT THE REAR AXLE
       ROLL CENTER)                                                       10
DEL30D=INITIAL VALUE OF SUSPENSION VELOCITY (FIRST TIME DERIVATIVE OF DELTA(3)10
DTCOMP=INCREMENT OF INTEGRATION                                            1
DTCMP1=0.0,PROGRAM COMPUTES INITIAL POSITION OF VEHICLE TO REST ON TERRAIN 1
      =1.0, USER PROVIDES ALL INITIAL POSITION DATA                        1
DTPRNT=OUTPUT INTERVAL                                                     1
 DRWHJ=INCREMENT VALUE OF R(W)-H'(J) FOR F'(J) TABLE                      16
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    EM=APPLICABLE ONLY IF MODE = 0, SEE PINT1 ROUTINE                            2
  EBAR=APPLICABLE ONLY IF MODE = 0, SEE PINT1 ROUTINE                            2
  EPSB=ACCEPTABLE ERROR IN FORCE BALANCE BETWEEN VEHICLE STRUCTURE AND BARRIER19
  EPSF=FRICTION LAG IN FRONT SUSPENSICN TO PREVENT EXTRANEOUS OSCILLATIONS
       INDUCED BY ROUND-OFF ERROR IN SUSPENSION VELOCITIES                       5
 EPSPS=FRICTION LAG IN STEERING SYSTEM                                          17
  EPSR=FRICTION LAG IN REAR SUSPENSION TO PREVENT EXTRANECUS OSCILLATIONS
       INDUCED BY ROUND-OFF ERROR IN SUSPENSION VELOCITIES                       6
  EPSV=FRICTION LAG IN VEHICLE-TO-BARRIER FRICTION FORCE
 FRFAC=COEFFICIENT OF FRICTION BETWEEN THE VEHICLE AND TERRAIN                  23
     G=386.4                                                                     3
  HMAX=APPLICABLE ONLY IF MODE = 0, SEE PINT1 ROUTINE                            2
  HMIN=APPLICABLE ONLY IF MODE = 0, SEE PINT1 ROUTINE                            2
  INDB=1.0 RIGID BARRIER FINITE VERTICAL DIM.                                   19
  INDB=2.0 RIGID BARRIER INFINITE VERTICAL DIM.                                 19
  INDB=3.0 DEFORMABLE BARRIER FINITE VERTICAL DIM.                              19
  INDB=4.0 DEFORMABLE BARRIER INFINITE VERTICAL DIM.                            19
INDCRB=0.0 NO CURB INPUT                                                         1
      =1.0 ACTIVATES STEER DEGREE OF FREEDOM AND RADIAL SPRING TIRE MODEL
       (CURB INPUT)                                                              1
      =-1.0 ACTIVATES STEER DEGREE ONLY (BARRIER INPUT)                          1
  ITEMP(I)=TEMPLATE NO. (I.E., 1,2,3.....21)                                    14
  MODE=MODE OF INTEGRATION=0.0 VARIABLE ADAMS-MOULTON                            2
                          =1.0 RUNGE-KUTTA                                       2
                          =2.0 FIXED ADAMS-MOULTON                               2
   NBX=NO. OF TEMPLATES ALONG X'-AXIS                                           14
   NBY=NO. OF POINTS IN Y' DIRECTION ON EACH TEMPLATE                           14
 NMUXY=NO. OF VARIABLE COEFFICIENT FRICTION PATCHES                             14
 NTBL1= =0.0 MEANS DO NOT READ PSI(F) TABLE                                     13
 NTBL2= =0.0 MEANS DO NOT READ TQ(F) TABLE                                      13
 NTBL3= =0.0 MEANS DO NOT READ TQ(R) TABLE                                      13
   NVP=NUMBER OF POINTS ON THE VEHICLE WHICH ARE TO BE MONITORED FOR CONTACT  23
       WITH THE GROUND
 OMEGF=MAXIMUM SUSPENSION DEFLECTIONS, FROM THE POSITION OF STATIC EQUILIBRIUM
       RELATIVE TO THE VEHICLE, FOR QUASI-LINEAR LOAD-DEFLECTION
       CHARACTERISTICS OF THE SPRINGS FOR FRONT SUSPENSION                       5
 OMEGR=MAXIMUM SUSPENSION DEFLECTIONS, FROM THE POSITION OF STATIC EQUILIBRIUM
```

```
      RELATIVE TO THE VEHICLE, FOR QUASI-LINEAR LOAD-DEFLECTION
      CHARACTERISTICS OF THE SPRINGS FOR REAR SUSPENSION                6
OMEGT=DECIMAL PORTION OF A(2)AT WHICH THE ASSUMED PARABOLIC VARIATION OF SIDE
      FORCE WITH TIRE LOADING IS ABANDONED TO PRECLUDE REVERSAL IN THE SIGN
      OF THE SIDE LOAD UNDER CONDITIONS OF EXCESSIVE TIRE LOADING       7
OMGPS=ANGULAR DEFLECTION OF THE STEERING SYSTEM AT WHICH ELASTIC STOPS ARE
      ENCOUNTERED                                                      17
 PHIC=FRONT WHEEL CAMBER                                               12
PHIC1=FIRST CURB SLOPE ECOUNTERED BY THE VEHICLE                       15
PHIC2=SECOND CURB SLOPE ENCOUNTERED BY THE VEHICLE                     15
PHILRO=INITIAL VALUE OF PHI(R) (ANGULAR DISPLACEMENT OF THE REAR AXLE
      RELATIVE TO THE VEHICLE ABOUT A LINE PARALLEL TO THE X-AXIS THROUGH
      THE REAR AXLE ROLL CENTER, POSITIVE WHEN CW VIEWED FROM REAR)    10
 PHIO=INITIAL VALUE OF PHI (EULER ANGULAR COORDINATES OF SPRUNG MASS RELATIVE
      TO SPACE-FIXED SYSTEM)                                            8
PHIROD=INITIAL VALUE OF ANGULAR VELOCITY OF REAR AXLE (FIRST TIME DERIVATIVE
      OF PHI(R)                                                        10
   PO=INITIAL VALUE OF P (SCALAR COMPONENT OF SPRUNG MASS ANGULAR VELOCITY,
      TAKEN ALONG X-AXIS                                                8
PQRMIN=STOPPING TEST=0.0                                                1
 PSIF=STEERING ANGLE OF FRONT WHEELS RELATIVE TO VEHICLE COORDINATE AXES 13
      SYSTEM, POSITIVE FOR CLOCK-WISE STEER AS VIEWED FROM ABOVE VEHICLE,
      DEGREES
PSIFDO=INITIAL VALUE OF STEERING ANGULAR VELOCITY (FIRST TIME DERIVATIVE OF
      PSI(F))                                                           8
PSIFIO=INITIAL VALUE OF PSI(F) (STEER ANGLE OF FRONT WHEELS RELATIVE TO VEHICLE
      COORDINATE AXES SYSTEM, POSITIVE FOR CW STEER AS VIEWED FROM ABOVE
      VEHICLE)                                                          8
 PSIO=INITIAL VALUE OF PSI (EULER ANGULAR COORDINATES OF SPRUNG MASS RELATIVE
      TO SPACE-FIXED SYSTEM)                                            8
   QO=INITIAL VALUE OF Q (SCALAR COMPONENT OF SPRUNG MASS ANGULAR VELOCITY,
      TAKEN ALONG Y-AXIS                                                8
   RF=AUXILIARY ROLL STIFFNESS AT THE FRONT SUSPENSION                  5
  RHO=DISTANCE BETWEEN C.G. OF REAR AXLE AND REAR AXLE ROLL CENTER, POSITIVE
      FOR ROLL CENTER ABOVE C.G.                                        4
   RO=INITIAL VALUE OF R (SCALAR COMPONENT OF SPRUNG MASS ANGULAR VELOCITY,
      TAKEN ALONG Z-AXIS                                                8
```

```
    RR=AUXILIARY ROLL STIFFNESS AT THE REAR SUSPENSION                          6
    RW=UNDEFLECTED RADIUS OF WHEELS                                             4
 RWHJB=INITIAL VALUE OF R(W)-H'(J) FOR F'(J) TABLE                             16
 RWHJE=FINAL VALUE OF R(W)-H'(J) FOR F'(J) TABLE                               16
   SET=RATIO OF PERMANENT DEFLECTION TO MAXIMUM DEFLECTION OF BARRIER          19
  SIGR=POLYNOMIAL COEFFICIENTS FOR BARRIER FORCE-DEFLECTION CURVE              20
  SIGT=MAXIMUM RADIAL TIRE DEFLECTION FOR QUASI-LINEAR LOAD-DEFLECTION
       CHARACTERISTIC                                                           7
SSTIFF=STIFFNESS OF EQUIVALENT GROUND SPRING                                   23
    TB=INITIAL TIME FOR DRIVER CONTROL INPUTS                                  13
    TE=FINAL TIME FOR DRIVER  CONTROL INPUTS                                   13
    TF=TREAD AT FRONT SUSPENSION                                                4
THETAO=INITIAL VALUE OF THETA (EULER ANGULAR COORDINATES OF SPRUNG MASS
       RELATIVE TO SPACE-FIXED SYSTEM)                                          8
 THMAX=VALUE OF THETA AT WHICH WE SHIFT PLANES USUALLY=70 DEGREES               1
 TINCR=INCREMENT TIME FOR DRIVER CONTROL INPUTS                                13
    TI=END TIME                                                                 1
    TO=START TIME                                                               1
   TQF=APPLIED TORQUE FOR A SINGLE FRONT WHEEL, EFFECTIVE  AT THE WHEEL        13
       (POSITIVE FOR TRACTION, NEGATIVE FOR BRAKING), LB.-FT.
   TQR=APPLIED TORQUE FOR A SINGLE REAR  WHEEL, EFFECTIVE  AT THE WHEEL        13
       (POSITIVE FOR TRACTION, NEGATIVE FOR BRAKING), LB.-FT.
    TR=TREAD AT REAR SUSPENSION                                                 4
    TS=DISTANCE BETWEEN SPRING CONNECTIONS FOR SOLID REAR AXLE                  6
    UO=INITIAL VALUE OF U (SCALAR COMPONENT  OF LINEAR VELOCITY OF SPRING
       MASS TAKEN ALONG X-AXIS)                                                 9
UVWMIN=STOPPING TEST=0.0                                                        1
    VO=INITIAL VALUE OF V (SCALAR COMPONENT  OF LINEAR VELOCITY OF SPRING
       MASS TAKEN ALONG Y-AXIS)                                                 9
    WO=INITIAL VALUE OF W (SCALAR COMPONENT  OF LINEAR VELOCITY OF SPRING
       MASS TAKEN ALONG Z-AXIS)                                                 9
    XB=INITIAL X' VALUE FOR TERRAIN TABLES                                     14
  XCOP=INITIAL VALUE OF X'(C) (COORDINATE OF THE SPRING MASS C.G. RELATIVE TO
       THE SPACE-FIXED COORDINATE AXES SYSTEM)                                  9
    XE=FINAL X' VALUE FOR TERRAIN TABLES                                       14
 XINCR=INCREMENT X' VALUE FOR TERRAIN TABLES                                   14
  XIPS=MOMENT OF INERTIA OF STEERING SYSTEM, EFFECTIVE AT FRONT WHEELS,
```

(BOTH SIDES INCLUDED) 17
XIR=REAR UNSPRUNG MASS MOMENT OF INERTIA ABOUT A LINE THROUGH ITS CENTER OF GRAVITY AND PARALLEL TO THE X-AXIS 3
XIX=MOMENT OF INERTIA OF SPRUNG MASS ABOUT X-AXIS 3
XIXZ=PRODUCT OF INERTIA OF SPRUNG MASS 3
XIY=MOMENT OF INERTIA OF SPRUNG MASS ABOUT Y-AXIS 3
XIZ=MOMENT OF INERTIA OF SPRUNG MASS ABOUT Z-AXIS 3
XJ=SOIL DAMPING CONSTANT 23
XLAMF=MULTIPLES OF AKF FOR USE IN SUSPENSION DEFLECTION STOPS 5
XLAMR=MULTIPLES OF AKR FOR USE IN SUSPENSION DEFLECTION STOPS 6
XLAMT=MULTIPLE OF AKT FOR USE IN NONLINEAR RANGE 7
XMUF=FRONT UNSPRUNG MASS (BOTH SIDES) 3
XMUR=REAR UNSPRUNG MASS 3
XMS=SPRUNG MASS 3
XPS=PNEUMATIC TRAIL OF FRONT TIRES 17
XTEMP(I)=X'(G) VALUE OF TEMPLATE ITEMP(I) 14
XVF=DISTANCE FROM C.G. OF VEHICLE TO FRONT OF VEHICLE MEASURED ALONG X-AXIS18
XVP(I)=X-COORDINATE OF POINT I ON THE VEHICLE, IN VEHICLE FIXED COORDINATES 23
XVR=DISTANCE FROM C.G. OF VEHICLE TO REAR OF VEHICLE MEASURED ALONG X-AXIS18
X1=COORDINATE OF ACCELEROMETER POSITION ON THE SPRUNG MASS, AT WHICH ACCELERATION COMPONENTS ARE TO BE CALCULATED AND PRINTED OUT (WITH REFERENCE TO THE VEHICLE FIXED AXIS) 11
X2=COORDINATE OF ACCELEROMETER POSITION ON THE SPRUNG MASS, AT WHICH ACCELERATION COMPONENTS ARE TO BE CALCULATED AND PRINTED OUT (WITH REFERENCE TO THE VEHICLE FIXED AXIS) 11
YB=INITIAL Y' VALUE FOR TERRAIN TABLES 14
YBPO=DISTANCE BETWEEN BARRIER PLANE AND THE X'-Z' PLANE 18
YCIP=INITIAL BOUNDARY OF CURB TO BE ENCOUNTERED BY VEHICLE (FIRST SLOPE CHANGE) 15
YCOP=INITIAL VALUE OF Y'(C) (COORDINATE OF THE SPRING MASS C.G. RELATIVE TO THE SPACE-FIXED COORDINATE AXES SYSTEM) 9
YC2P=BOUNDARY OF SECOND SLOPE OF CURB 15
YE=FINAL Y' VALUE FOR TERRAIN TABLES 14
YINCR=INCREMENT Y' VALUE FOR TERRAIN TABLES 14
YGP(I,J)=Y'(G) VALUE OF POINT J=1 ON TEMPLATE I TEMPLATE ITEMP(I) 14
YGP(I,J+1)=Y'(G) VALUE OF POINT J=2 ON TEMPLATE ITEMP(I) 14
YV=DISTANCE FROM C.G. OF VEHICLE TO EITHER SIDE OF VEHICLE MEASURED ALONG

THE Y-AXIS 18

YVP(I)=Y-COORDINATE OF POINT I ON THE VEHICLE, IN VEHICLE FIXED COORDINATES 23

Y1=COORDINATE OF ACCELEROMETER POSITION ON THE SPRUNG MASS, AT WHICH ACCELERATION COMPONENTS ARE TO BE CALCULATED AND PRINTED OUT (WITH REFERENCE TO THE VEHICLE FIXED AXIS) 11

Y2=COORDINATE OF ACCELEROMETER POSITION ON THE SPRUNG MASS, AT WHICH ACCELERATION COMPONENTS ARE TO BE CALCULATED AND PRINTED OUT (WITH REFERENCE TO THE VEHICLE FIXED AXIS) 11

ZBBP=THE ELEVATION OF THE BOTTOM OF THE BARRIER RELATIVE TO THE X'-Y' PLANE 18

ZBTP=THE ELEVATION OF THE TOP OF THE BARRIER RELATIVE TO THE X'-Y' PLANE 18

ZCOP=INITIAL VALUE OF Z'(C) (COORDINATE OF THE SPRING MASS C.G. RELATIVE TO THE SPACE-FIXED COORDINATE AXES SYSTEM) 9

ZC2P=ELEVATION OF CURB PROFILE AT YC2P 15

ZF=STATIC DISTANCE ALONG THE Z-AXIS BETWEEN THE C.G. OF THE SPRUNG MASS AND THE C.G.OF THE FRONT UNSPRUNG MASSES 4

ZGP(I,J)=Z'(G) VALUE OF POINT J=1 ON TEMPLATE ITEMP(I) 14

ZGP(I,J+2)=Z'(G) VALUE OF POINT J=2 ON TEMPLATE ITEMP(I) 14

ZR=STATIC DISTANCE ALONG THE Z-AXIS BETWEEN THE C.G. OF THE SPRUNG MASS AND THE ROLL CENTER OF THE REAR AXLE 4

ZVB=DISTANCE FROM C.G. OF VEHICLE TO BOTTOM OF VEHICLE MEASURED ALONG Z-AXIS 18

ZVP(I)=Z-COORDINATE OF POINT I ON THE VEHICLE, IN VEHICLE FIXED COORDINATES 23

ZVT=DISTANCE FROM C.G. OF VEHICLE TO TOP OF VEHICLE MEASURED ALONG Z-AXIS 18

Z1=COORDINATE OF ACCELEROMETER POSITION ON THE SPRUNG MASS, AT WHICH ACCELERATION COMPONENTS ARE TO BE CALCULATED AND PRINTED OUT (WITH REFERENCE TO THE VEHICLE FIXED AXIS) 11

Z2=COORDINATE OF ACCELEROMETER POSITION ON THE SPRUNG MASS, AT WHICH ACCELERATION COMPONENTS ARE TO BE CALCULATED AND PRINTED OUT (WITH REFERENCE TO THE VEHICLE FIXED AXIS) 11

APPENDIX C

APPENDIX C - LIST OF PROGRAM VARIABLES

FORTRAN NAME	PROGRAM VARIABLE		DESCRIPTION
A,B	a, b	=	distances along the vehicle-fixed axis from the sprung mass center of gravity to the center lines of the front and rear wheels, respectively, inches.
A0,A1,A2,A3,A4	A_o, A_1, A_2, A_3, A_4	=	constant coefficients in parabolas fitted to tire side-force properties.
AMTX	$\|A\|$	=	matrix for transformations from the vehicle-fixed coordinate system to the space-fixed coordinate system.
	$\|A^T\|$	=	transpose of $\|A\|$. Note that the transpose and the inverse of $\|A\|$ are identical, since $\|A\|$ is orthogonal.
	$(A_{INT})_i$	=	intersection area of cutting plane i with the sprung mass, in^2.
	C_{co}	=	small-angle camber stiffness, lbs/radian.
	C_{so}	=	small-angle cornering stiffness, lbs/radian.
CF,CR	C_F, C_R	=	viscous damping coefficient for a single wheel, effective at the wheel for the front and at the spring for the rear suspension, at the front and rear, respectively, lb-sec/in.
CFP,CRP	C_F', C_R'	=	coulomb damping for a single wheel, effective at the wheel for the front and at the spring for the rear suspension, at the front and rear, respectively, lbs.

CPSF	C'_{ψ}	=	coulomb resistance in steering system, effective at the wheels (both sides included), lb-in.
	$\left.\begin{matrix} a_i \\ b_i \\ c_i \end{matrix}\right\}$	=	directional components of a line perpendicular to both the normal to the wheel plane and the radial tire force, F_{R_i} .
	$\left.\begin{matrix} a'_i \\ b'_i \\ c_i \end{matrix}\right\}$	=	directional components of lines in the cutting plane i , perpendicular to the line between $(X_1, Y_1, Z_1)_i$ and $(X_2, Y_2, Z_2)_i$.
AS,BS,CS	$a_{s_i}, b_{s_i}, c_{s_i}$	=	direction components of a line perpendicular both to a normal to the tire-terrain contact plane and to the wheel axis, X_{w_i} , at wheel i .
AX,BX,CX	$a_{x_i}, b_{x_i}, c_{x_i}$	=	direction components of a line perpendicular both to a normal to the tire-terrain contact plane and to the vehicle-fixed Y axis, at wheel i .
AY,BY,CY	$a_{y_i}, b_{y_i}, c_{y_i}$	=	direction components of a line perpendicular both to a normal to the tire-terrain contact plane and the vehicle-fixed X axis, at wheel i .
CONS	$\overline{CONS}$	=	ratio of conserved energy to maximum energy absorbed by barrier.
D1,D2,D3	$D_{1_i}, D_{2_i}, D_{3_i}$	=	direction components of a line perpendicular to the normals of both the wheel plane and the tire-terrain contact plane, at wheel i .
	F_B	=	resistance force measured normal to the contact surface of a deformable barrier, lbs.
FC	F_{c_i}	=	circumferential tire force (i.e., tractio or braking force) at wheel i , lbs.

	$(F_N)_t$	=	vehicle force produced by deformation of vehicle structure, measured normal to contacted surface, lbs.
FR	F_{R_i}	=	radial tire force at wheel i, lbs.
FRCP	F'_{R_i}	=	tire force perpendicular to the tire-terrain contact plane at wheel i, lbs.
	$\overline{FRICT}$	=	friction force acting between the vehicle sprung mass and a barrier.
FS	F_{s_i}	=	tire side force in the plane of the tire-terrain contact patch, perpendicular to the line of intersection of the wheel and ground planes at wheel i, lbs.
F1FI,F1RI	F_{1F_i}, F_{1R_i}	=	coulomb damping forces in front and rear suspensions, at an indivudual wheel, effective at wheels in front and at spring locations in rear, lbs.
F2FI,F2RI	F_{2F_i}, F_{2R_i}	=	suspension forces produced by deflection of springs and elastic travel limits, lbs.
FCXU FCYU FCZU	$\left.\begin{matrix} F_{cxu_i} \\ F_{cyu_i} \\ F_{czu_i} \end{matrix}\right\}$	=	components of the circumferential tire force at wheel i along the sprung mass X, Y, Z axes, lbs.
FRXU FRYU FRZU	$\left.\begin{matrix} F_{Rxu_i} \\ F_{Ryu_i} \\ F_{Rzu_i} \end{matrix}\right\}$	=	components of F'_{R_i} at wheel i along the sprung mass X, Y, Z axes, lbs.
FSXU FSYU FSZU	$\left.\begin{matrix} F_{sxu_i} \\ F_{syu_i} \\ F_{szu_i} \end{matrix}\right\}$	=	components of tire side force, F_{s_i}, at wheel i along the sprung mass X, Y, Z axes, lbs.
SFXS SFYS SFZS	$\left.\begin{matrix} \sum F_{xs} \\ \sum F_{ys} \\ \sum F_{zs} \end{matrix}\right\}$	=	components of sprung mass impact force along the sprung mass axes, lbs.

FXU FYU FZU	$F_{Xui}, F_{Yui}, F_{Zui}$	= tire force components along vehicular axes, lbs.
	F_{c_i}'	= value of circumferential tire force that is used in approximating the effects of differential gears, at wheel i , lbs.
	F_{s_i}'	= tire side force for small slip angles and for "equivalent" slip angles that approximate camber effects, at wheel i , lbs.
	$(F_{si})_{max}$	= Maximum possible tire side force at wheel i , lbs.
GAIN	(GAIN)	= closed-loop steer control parameter, radians/inch.
G	g	= acceleration of gravity = 386.4 in/sec^2
HI	h_i	= rolling radius of wheel i , inches.
XIR	I_R	= rear unsprung mass moment of inertia about a line through its center of gravity and parallel to the X axis, lb-sec^2-in.
XIX,XIY,XIZ,XIXZ	I_X, I_Y, I_Z, I_{XZ}	= moments and product of inertia of sprung mass, lb-sec^2-in.
	i	= wheel identification-- 1, 2, 3, 4 = RF, LF, RR, LR, respectively.
XIPS	I_ψ	= moment of inertia of steering system effective at front wheels (both sides included), lb-sec^2-in.
AKF,AKR	K_F, K_R	= suspension load-deflection rate for a single wheel in the quasi-linear range about the design position, effective at the wheel for the front and at the spring for the rear suspension, at the front and rear, respectively, lb/in.

AKT	K_T	=	radial tire rate in quasi-linear range for a single tire, lb/in.
AKRS	K_{RS}	=	rear axle roll-steer coefficient (positive for roll understeer)
AKPS	K_ψ	=	load deflection rate of elastic stops in the steering system, effective at the wheels (both sides included), lb-in/rad, reference Fig. C-1.
AKV	K_V	=	load-deflection characteristic of vehicle structure, lb/in^3.
DELPTH	m	=	time increment between sampling times for closed-loop steer control, sec.
XMS	M_s	=	sprung mass, lb-sec^2/in.
XMUF	M_{uF}	=	front unsprung mass (both sides), lb-sec^2/in.
	$M_1 = M_2 = \frac{M_{uF}}{2}$	=	front unsprung mass at a single wheel, lb-sec^2/in.
XMUR	$M_3 = M_{uR}$	=	rear unsprung mass, lb-sec^2/in.
	$\left.\begin{matrix}\Sigma N_{\phi s}\\ \Sigma N_{\theta s}\\ \Sigma N_{\psi s}\end{matrix}\right\}$	=	components of moments on sprung mass produced by sprung mass impact forces, lb-in.
	$\left.\begin{matrix}N_{\phi u}\\ N_{\theta u}\\ N_{\psi u}\end{matrix}\right\}$	=	moments produced by forces acting on the unsprung masses, lb-in.
	$N_{\phi R}$	=	rolling moment acting on the rear axle, lb-in.
P,Q,R	P, Q, R	=	scalar components of sprung mass angular velocity, taken along X , Y , Z axes, respectively, radians/sec.
XPS	$\overline{PT}$	=	pneumatic trail of front tires, inches.

RF,RR	R_F, R_R	= auxiliary roll stiffness (i.e., roll stiffness in excess of that corresponding to the front wheel rates in ride and to the rear spring rates and spacing), at the front and rear suspensions, respectively, lb-in/radian.
RW	R_W	= undeflected radius of wheels, inches.
	$\left.\begin{matrix} R_{Bi} \\ R_{BT} \\ R_{BB} \end{matrix}\right\}$	= constants for barrier face plane, top plane and bottom plane, in.
	$(S_1)_i, (S_2)_i, (S_3)_i$	= the two heights and base, respectively, of the triangles used in calculation of the intersection area at cutting plane i, in.
SET	$\overline{SET}$	= ratio of permanent deflection to maximum deflection of barrier.
SI	S_i	= total suspension force produced by the combination of springs, travel stops, viscous damping, friction, and auxiliary roll stiffness, effective at the wheel for the front suspension and at the spring location for the rear suspension, at wheel i, lbs.
	SP_1 through SP_{30}	= polynomial coefficients for curves defining desired vehicle path.
	t	= time, seconds.
DELTC	$(\Delta t)_c$	= time increment size used during curb contact, sec.
TF,TR	T_F, T_R	= tread at front and rear suspensions, respectively, inches.
TI	T_i	= circumferential tire force corresponding to the applied torque at wheel i, which is subjected to force-limiting logic, lbs.

TQF,TQR $\overline{TQ}_F$, $\overline{TQ}_R$ = tabular inputs of applied torque for a single wheel, effective at the wheel, for front and rear wheels, respectively (positive for traction, negative for braking), lb-ft.

TS T_s = distance between spring connections for solid rear axle, inches.

$T_{1\psi}$ = coulomb friction torque in steering system, effective at wheel i , lb-in.

$T_{2\psi}$ = resistance torque produced by front wheel steer angle stops, effective at wheel i , lb-in.

U,V,W u, v, w = scalar components of linear velocity of the sprung mass, taken along the X , Y , Z axes, respectively, inches/sec.

u', v', w' = scalar components of linear velocity of sprung mass, taken along space-fixed X', Y' , Z' axes, respectively, inches/sec.

UG u_{G_i} = forward velocity of wheel center in the direction parallel to the tire-terrain contact plane, inches/sec.

$|u_{G_i}|$ = absolute value of u_{G_i}.

$1 \ \mathrm{sgn} \ u_{G_i}$ = algebraic sign of u_{G_i} .

u'_n, v'_n, w'_n = scalar components of the velocity of the three or four points that define the intersection area of the barrier and the vehicle along the space-fixed axes, in/sec.

	u'_R, v'_R, w'_R	= scalar components of the velocity of the point of application of the sprung mass contact force along the space-fixed axes, in/sec.
VG	v_{G_i}	= lateral velocity of the contact point of wheel i in the direction parallel to the tire-terrain contact plane, inches/sec.
	$\overline{VTAN}$	= velocity of the point of application of the sprung mass impact force tangential to the barrier, in/sec.
	X_{VP}	= vehicle reference dimension for closed-loop steer control, inches.
	X, Y, Z	= coordinates of a point relative to the vehicle-fixed coordinate axes system, inches.
	X', Y', Z'	= coordinates of a point relative to the space-fixed coordinate axes system, inches.
X1,Y1,Z1 X2,Y2,Z2	$\left.\begin{matrix} X_1, Y_1, Z_1 \\ X_2, Y_2, Z_2 \end{matrix}\right\}$	= coordinates of accelerometer positions on the sprung mass, at which acceleration components are to be calculated and printed out, inches.
	$X_{B_i}, Y_{B_i}, Z_{B_i}$	= coordinates of the intersection of the Y' axis with barrier cutting plane i, in the vehicle-fixed axes, inches.
X	X_{BT}, Y_{BT}, Z_{BT}	= coordinates of the intersection of the Z' axis with the barrier top plane in the vehicle-fixed axes, inches.
	X_{BB}, Y_{BB}, Z_{BB}	= coordinates of the intersection of the Z' axis with the barrier bottom plane in the vehicle-fixed axes, inches.

	$X'_{cpn}, Y'_{cp}, Z'_{cpn}$	= coordinates of vehicle corner point n in the space-fixed axes, inches.
XCP,YCP,ZCP	X'_c, Y'_c, Z'_c	= coordinates of the sprung mass center of gravity relative to the space-fixed coordinate axes system, inches.
	$(X_R)_i, (Y_R)_i, (Z_R)_i$	= coordinates of the centroid of the intersection area on barrier cutting plane i , projected onto the actual vehicle-barrier interface of the previous time increment, inches.
	$(\Sigma X_R)_t, (\Sigma Y_R)_t, (\Sigma Z_R)_t$	= the coordinates of the point of application of the sprung mass impact forces, inches.
	Y'_B	= Y' coordinate of barrier face plane, inches.
YCIP	Y'_{c1}	= initial boundary of curb to be encountered by vehicle, inches.
XC2P	Y'_{c2}	= boundary of second slope change of curb, inches.
	$Y'_{P1}, Y'_{P2}, Y'_{P3}, Y'_{P4}$	= transition boundaries for polynomial curves defining desired vehicle path, inches.
ZC2P	Z'_{c2}	= elevation of curb profile at Y'_{c2} .
XGPP,YGPP,ZGPP	$X'_{GPi}, Y'_{GPi}, Z'_{GPi}$	= coordinates of the "ground contact point" of wheel i relative to the space-fixed coordinate axes system, inches.
ZF	Z_F	= static distance along the Z axis between the center of gravity (c.g.) of the sprung mass and the c.g. of the front unsprung masses (c.g. of the individual front masses assumed to coincide with the wheel centers), inches.

ZR	Z_R	=	static distance along the Z axis between the c.g. of the sprung mass and the roll center of the rear axle, inches.
ZPGI	Z'_{Gi}	=	ground elevation with respect to space-fixed Z' axis, under the center of wheel i, inches.
	$\bar{Z}'_{Gi}$	=	a vector through the ground contact point, normal to the actual or "equivalent" tire-terrain contact plane, at wheel i (Fig. 4.4, Ref. 3).
XVF,XVR,YV,ZVT,ZVB	$\left.\begin{matrix} X_{VF}, X_{VR}, Y_V \\ Z_{VT}, Z_{VB} \end{matrix}\right\}$	=	vehicle dimensions for sprung mass impact, inches.
ZBTP,ZBBP	Z'_{BT}, Z'_{BB}	=	elevations of barrier top and bottom planes for sprung mass impact, inches.
CAB CBB CGB	$\left.\begin{matrix} \cos\alpha_B \\ \cos\beta_B \\ \cos\gamma_B \end{matrix}\right\}$	=	directional cosines of a normal to the barrier face plane relative to the vehicle-fixed axes.
	$\left.\begin{matrix} \cos\alpha_B \\ \cos\beta_B \\ \cos\gamma_B \end{matrix}\right\}$	=	directional cosines of a normal to the barrier top and bottom planes relative to the vehicle-fixed axes.
CAC CBC CGC	$\left.\begin{matrix} \cos\alpha_{ci} \\ \cos\beta_{ci} \\ \cos\gamma_{ci} \end{matrix}\right\}$	=	direction cosines of a line perpendicular to the normals both of the wheel plane and the tire-terrain contact plane at wheel i.
CAGZ CBGZ CGGZ	$\left.\begin{matrix} \cos\alpha_{GZ'i} \\ \cos\beta_{GZ'i} \\ \cos\gamma_{GZi} \end{matrix}\right\}$	=	direction cosines of a normal to the tire-terrain contact plane at wheel i.
CAH CBH CGH	$\left.\begin{matrix} \cos\alpha_{hi} \\ \cos\beta_{hi} \\ \cos\gamma_{hi} \end{matrix}\right\}$	=	directional cosines of the resultant radial force on wheel i, with respect to the vehicle-fixed axes.

	$\cos \alpha_j$ $\cos \beta_j$ $\cos \gamma_j$	= directional cosines of a line to wheel center i, from the point of contact with the ground (or curb) of radial spring j, relative to the space-fixed axes.
CAR CBR CGR	$\cos \alpha_{Ri}$ $\cos \beta_{Ri}$ $\cos \gamma_{Ri}$	= direction cosines of the resultant radial force on wheel i, with respect to the space-fixed axes.
CAS CBS CGS	$\cos \alpha_{si}$ $\cos \beta_{si}$ $\cos \gamma_{si}$	= direction cosines of a line perpendicular both to a normal to the tire-terrain contact plane and to the wheel axis, X_{wi}, at wheel i.
CAX CBX CGX	$\cos \alpha_x$ $\cos \beta_x$ $\cos \gamma_x$	= direction cosines of X axis.
CAY CBY CGY	$\cos \alpha_y$ $\cos \beta_y$ $\cos \gamma_y$	= direction cosines of Y axis.
CAYW CBYW CGYW	$\cos \alpha_{Ywi}$ $\cos \beta_{Ywi}$ $\cos \gamma_{Ywi}$	= direction cosines of a normal to the plane of wheel i.
CAZW CBZW CGZW	$\cos \alpha_{Zwi}$ $\cos \beta_{Zwi}$ $\cos \gamma_{Zwi}$	= directional cosines of the kingpin axis of wheel i (kingpin axis assumed to lie in wheel plane)
BET	β_i	= slip angle at wheel i, radians.
BETBR	$\bar{\beta}_i$	= non-dimensional slip angle variable for wheel i.
BETP	β'_i	= "equivalent slip angle" produced by camber effects at wheel i, radians.
	$f(\bar{\beta}_i)$	= non-dimensional side force at wheel i.

	δ_B	= barrier deflection, inches.
	$\Delta y'_B$	= size of increment between barrier cutting planes, i, inches.
DELTA	Δ_i	= distance from the center of wheel i to the "ground contact point", inches.
DEL1,DEL2,DEL3	$\delta_1, \delta_2, \delta_3$	= suspension deflections relative to the vehicle from the positions of static equilibrium, at the right front wheel center, left front wheel center, and rear axle roll center, respectively, inches.
	ϵ_n	= permanent set of barrier, inches.
EPSB	ϵ_B	= acceptable error in force balance between vehicle structure and barrier, lbs.
EPSF,EPSR	ϵ_F, ϵ_R	= friction lag in front and rear suspensions, respectively, to prevent extraneous oscillations induced by round-off error in suspension velocities, in/sec.
EPSV	ϵ_V	= friction lag in vehicle-to-barrier friction force, in/sec.
EPSPS	ϵ_ψ	= friction lag in steering system, rad/sec.
	$(\zeta_0)_n, (\zeta_1)_n, (\zeta_2)_n$	= coefficients for parabolic form of barrier load-deflection characteristics for barrier unloading.
ZETA3,ZETA4	ζ_3, ζ_4	= suspension deflections relative to the vehicle, from the positions of static equilibrium, measured at the right rear and left rear spring positions, respectively, inches.

	ϕ, θ, ψ	=	Euler angular coordinates of sprung mass relative to the space-fixed axis system, radians.
	ϕ', θ', ψ'	=	Euler angular coordinates of sprung mass relative to indexed intermediate reference axes systems (i.e., to permit unrestricted ranges of angular travel), radians.
	θ_{XGi}	=	angle between X-axis and tire-terrain contact plane at wheel i, radians.
PHGI,THGI	ϕ_{Gi}, θ_{Gi}	=	Euler angular coordinates of terrain profile relative to the space-fixed axis system, under the center of wheel i, radians.
XLAMF,XLAMR	λ_F, λ_R	=	multiples of K_F, K_R, respectively, for use in suspension deflection stops (Fig. 4.15, Ref. 3).
XLAMT	λ_T	=	multiple of K_T for use in nonlinear range of tire deflection (i.e., travel limit).
AMU	μ	=	tire-to-ground friction coefficient.
AMUC	μ_c	=	tire-to-curb friction coefficient.
AMUB	μ_B	=	sprung mass-to-barrier friction coefficient.
AMUI	μ_i	=	tire-to-ground friction coefficient (dependent on tire location on terrain surface).
AMUXY	μ_{XY}	=	tire-to-ground friction coefficient (variable over terrain surface).

RHO ρ = distance between center of gravity of rear axle and rear axle roll center, positive for roll center above c.g., inches.

SIGT σ_T = maximum radial tire deflection for quasi-linear load-deflection characteristic, inches.

SIGR σ_R = coefficients for polynomial form of barrier load-deflection characteristics (for increasing loading).

PHIC1,PHIC2 ϕ_{c1}, ϕ_{c2} = first and second curb slopes encountered by the vehicle, radians.

PHIR ϕ_R = angular displacement of the rear axle relative to the vehicle about a line parallel to the X-axis through the rear axle roll center (positive when clockwise as viewed from the rear), radians.

PHI1, PHI2 ϕ_1, ϕ_2 = right front and left front wheel camber angles, respectively, relative to the vehicle-fixed coordinate axes (positive when clockwise as viewed from the rear), radians.

$$\left[\begin{array}{ll} \phi_1 & = \phi_c \text{, evaluated for } \delta_f = \delta_1 \text{ (RF wheel).} \\ \phi_2 & = -\phi_c \text{, evaluated for } \delta_f = \delta_2 \text{ (LF wheel).} \\ & \text{where } \phi_c \text{ vs } \delta_f = \text{Tabular Input.} \end{array}\right]$$

ϕ_{YGi} = angle between Y-axis and tire-terrain contact plane at wheel i, radians.

ϕ_{CGi} = camber angle of wheel i relative to its tire-terrain contact plane, radians.

PSIF,PSIF1,PSIF2 $\psi_f = \psi_1 = \psi_2$ = steer angle of front wheels relative to vehicle coordinate axes system, positive for clockwise steer as viewed from above vehicle (assumed equal at the two wheels), radians.

$\psi_3 = \psi_4 \; (= K_{RS}\phi_R)$ = steer angle of rear wheels relative to vehicle coordinate axes system, positive for CW steer as viewed from above vehicle, radians.

PSIIP ψ_i' = steer angle of wheel i in its tire-terrain contact plane, radians.

OMEGAF,OMEGAR Ω_F, Ω_R = maximum suspension deflections, from the positions of static equilibrium relative to the vehicle, for quasi-linear load-deflection characteristics of the springs (Fig. 4.15, Ref.3), inches.

OMGPS Ω_ψ = angular deflection of the steering system at which elastic stops are encountered, radians, reference Fig. C-1.

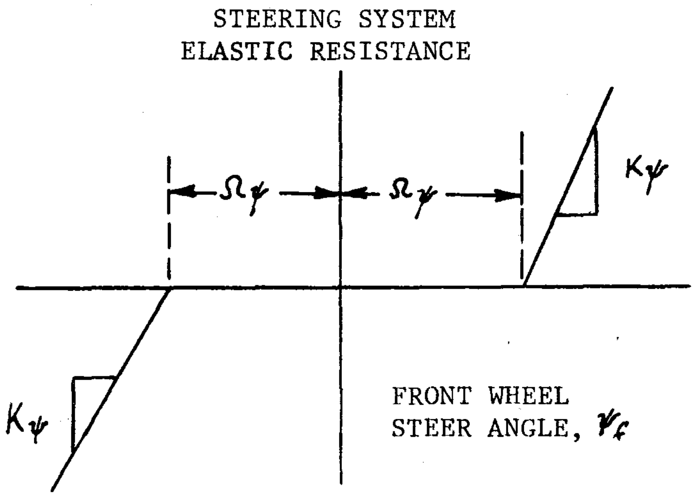


Figure C-1 STEERING SYSTEM ELASTIC RESISTANCE VS STEER ANGLE

OMEGT	Ω_T	= multiple of A_2 at which the assumed parabolic variations of small-angle cornering and camber stiffnesses with tire loading are abandoned to preclude reversal in the sign of the side force under conditions of excessive tire loading.

APPENDIX D

Appendix D - Derivation of Vehicle-Ground Interaction

Inevitably, for certain combinations of vehicle-maneuvers and terrain configurations, the vehicle body must come in contact with the terrain. To incorporate the effect of this occurrence in the vehicle's response, subroutine "VGCP" has been added to the original CALSVA program.

This subroutine essentially monitors certain points on the vehicle, selected and input by the user as explained in Part 2.1. Whenever any of the chosen vehicle-points engage the terrain, contact forces are computed and transferred to the center of gravity of the vehicle. The magnitudes of these forces depend on soil stiffness, soil damping characteristics, depth of penetration and velocity of the vehicle-point in question.

It was decided, after trying other ideas, that the soil should impart only two forces to the vehicle at the point in contact, namely a force normal to the terrain surface and a frictional force tangent to the terrain surface. To compute the magnitudes and directions of these two forces, the following parameters are needed:

(1) The amount of soil penetration, in a direction normal to the terrain surface, at the point of contact,

(2) The velocity vector of the point on the vehicle, in a direction normal to the terrain surface,

(3) The velocity vector of the point on the vehicle, in a direction tangent to the terrain surface.

The derivation of each of these parameters follows, and in each case, the actual Fortran names of the variables are used.

Amount of Soil Penetration Normal to Terrain

Consider a point "I" on the vehicle body defined by coordinates XVP(I), YVP(I), and ZVP(I) in vehicle-fixed coordinates,

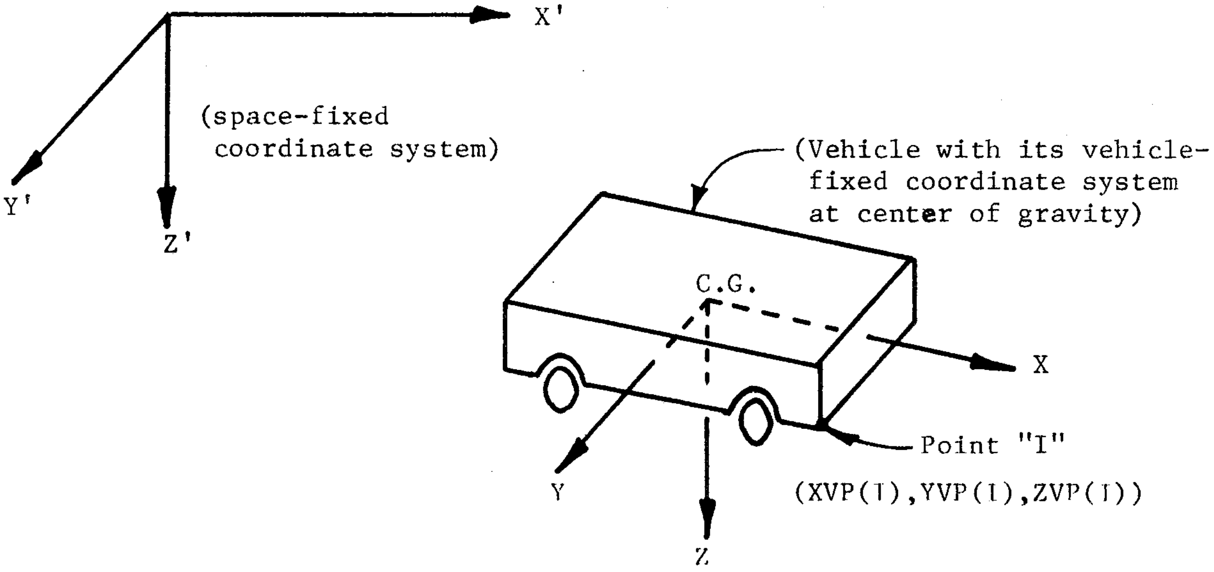


Figure D-1. Coordinate Systems

The coordinates of the vehicle point "I" in space-fixed coordinates (XVPP(I), YVPP(I), ZVPP(I)) are obtained by:

$$\begin{Bmatrix} XVPP(I) \\ YVPP(I) \\ ZVPP(I) \end{Bmatrix} = \begin{bmatrix} & & \\ & AMTX & \\ & & \end{bmatrix} \begin{Bmatrix} XVP(I) \\ YVP(I) \\ ZVP(I) \end{Bmatrix} + \begin{Bmatrix} X'_c \\ Y'_c \\ Z'_c \end{Bmatrix}$$

AMTX is a transformation matrix used to transform from vehicle-fixed to space-fixed coordinates (see page 185, Ref. 3). X'_c, Y'_c, and Z'_c are the coordinates of the vehicle center of gravity in the space-fixed system.

Now consider a top view (X'-Y' plane) of the terrain (Fig. D-2) assuming that the vehicle point "I" lies somewhere between terrain template (J) and terrain template (J+1), and points (K) and (K+1) on these two templates. Let the point "PT" represent the point on the terrain directly above or below (depending on whether contact occurs) the point "I" on the vehicle. The coordinates of point "PT", in the space-fixed coordinate system, are defined as XXX, YYY, and ZVPPGI; therefore it necessarily follows that:

XXX = XVPP(I)

YYY = YVPP(I)

ZVPPGI = terrain elevation corresponding to XXX and YYY (computed)

Points P1 and P2 with coordinates as shown in Fig. D-2 are also computed based on input terrain information. With these three points (PT, P1, P2), two vectors which lie on the terrain surface and extend from point PT may be defined as follows:

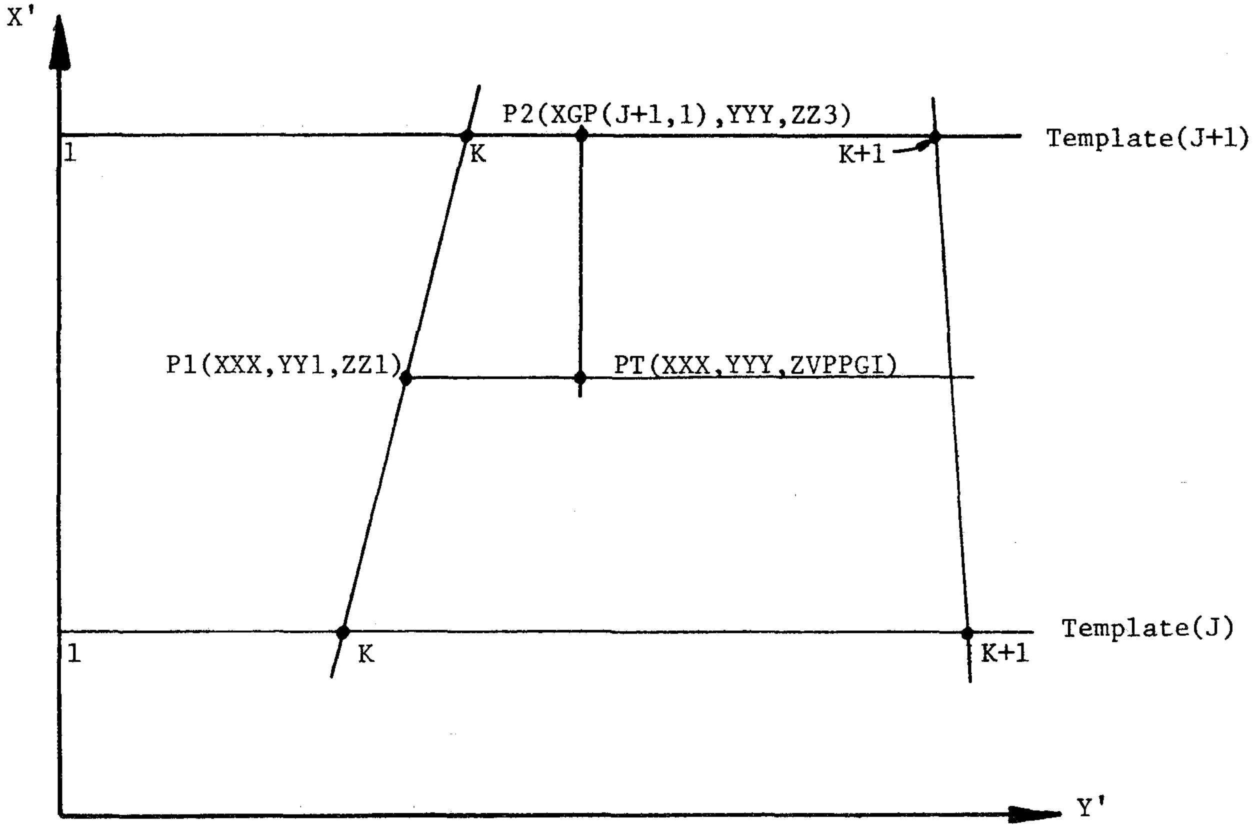


Figure D-2. TOP VIEW OF TERRAIN

$$\overline{PT\ P1} = (XXX\text{-}XXX)\bar{I} + (YY1\text{-}YYY)\bar{J} + (ZZ1\text{-}ZVPPGI)\bar{K}$$

or,

$$\overline{PT\ P1} = (YY1\text{-}YYY)\bar{J} + (ZZ1\text{-}ZVPPGI)\bar{K}$$

$$\overline{PT\ P2} = (XGP(J+1,1)\text{-}XXX)\bar{I} + (YYY\text{-}YYY)\bar{J} + (ZZ3\text{-}ZVPPGI)\bar{K}$$

or,

$$\overline{PT\ P2} = (XGP(J+1,1)\text{-}XXX)\bar{I} + (ZZ3\text{-}ZVPPGI)\bar{K}$$

NOTE: $\bar{I}$, $\bar{J}$, and $\bar{K}$ represent unit vectors parallel to X', Y', and Z', respectively.

Let $\bar{N} = \overline{PT\ P1} \times \overline{PT\ P2}$, the inward normal vector to the terrain surface at point PT.

Thus

$$\bar{N} = \begin{vmatrix} \bar{I} & \bar{J} & \bar{K} \\ 0 & (YY1\text{-}YYY) & (ZZ1\text{-}ZVPPGI) \\ (XGP(J+1,1)\text{-}XXX) & 0 & (ZZ3\text{-}ZVPPGI) \end{vmatrix}$$

or

$$\bar{N} = (YY1\text{-}YYY)(ZZ3\text{-}ZVPPGI)\bar{I} + (XGP(J+1,1)\text{-}XXX)(ZZ1\text{-}ZVPPGI)\bar{J}$$
$$- (XGP(J+1,1)\text{-}XXX)(YY1\text{-}YYY)\bar{K}$$

Since XVPP(I) = XXX and YVPP(I) = YYY,

$$\bar{N} = (YY1\text{-}YVPP(I))(ZZ3\text{-}ZVPPGI)\bar{I} + (XGP(J+1,1)\text{-}XVPP(I))(ZZ1\text{-}ZVPPGI)\bar{J}$$
$$- (XGP(J+1,1)\text{-}XVPP(I))(YY1\text{-}YVPP(I))\bar{K}$$

For convenience define:

$$\left.\begin{aligned} AA &= (YY1-YVPP(I))(ZZ3-ZVPPGI) \\ BB &= (XGP(J+1,1)-XVPP(I))(ZZ1-ZVPPGI) \\ CC &= (XGP(J+1,1)-XVPP(I))(YY1-YVPP(I)) \end{aligned}\right\} \qquad (D\text{-}1)$$

and $\bar{N} = (AA)\bar{I} + (BB)\bar{J} + (CC)\bar{K}$

From Equations D-1, it is now possible to define the equation of a plane which is tangent to the terrain surface at point PT, and the equation of a line which is normal to the terrain surface, passing through point "I" on the vehicle (Fig. D-3).

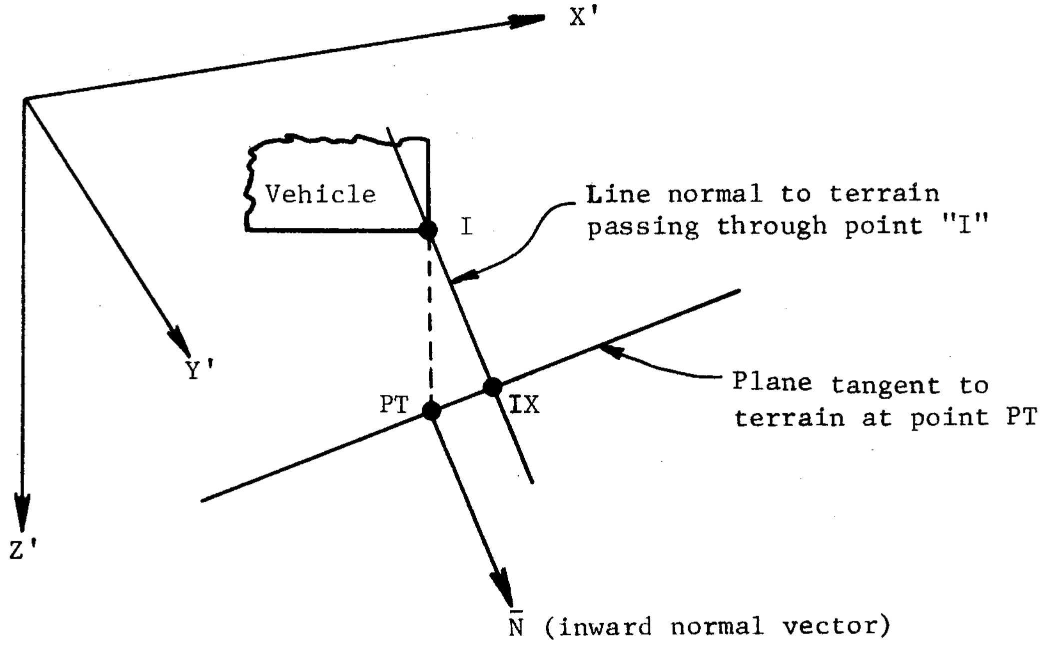


Figure D-3. Tangent Plane, Normal Line

The equation of the plane, passing through point PT, having $\bar{N}$ for a normal is

$$(AA)X' + (BB)Y' + (CC)Z' = G \qquad (D\text{-}2)$$

where $G = AA(XVPP(I)) + BB(YVPP(I)) + CC(ZVPPGI).$

The equation of the line passing through vehicle point "I" and parallel to $\bar{N}$ is

$$\frac{X' - XVPP(I)}{AA} = \frac{Y'-YVPP(I)}{BB} = \frac{Z' - ZVPP(I)}{CC} \qquad (D\text{-}3)$$

Solving equations D-2 and D-3 simultaneously yields the coordinates of point "IX" shown in Fig. D-3, i.e., the point of intersection of the line and plane in question. These coordinates are

$$\left.\begin{aligned} X'_{IX} &= XVPP(I) + \frac{(AA)(XL)}{H} \\ Y'_{IX} &= YVPP(I) + \frac{(BB)(XL)}{H} \\ Z'_{IX} &= ZVPP(I) + \frac{(CC)(XL)}{H} \end{aligned}\right\} \qquad (D\text{-}4)$$

where, $XL = CC(ZVPPGI-ZVPP(I))$

and $H = (AA)^2 + (BB)^2 + (CC)^2$

To find the distance, DLTVG, between points "I" and "IX" (Fig. D-3), define

$$\overline{IIX} = (X'_{IX}-XVPP(I))\bar{I} + (Y'_{IX}-YVPP(I))\bar{J} + (Z'_{IX}-ZVPP(I))\bar{K}$$

or

$$\overline{IIX} = \frac{XL}{H}((AA)\bar{I}+(BB)\bar{J}+(CC)\bar{K})$$

DLTVG is determined by $|\overline{IIX}|$. Hence,

$$DLTVG = \frac{XL}{H} \cdot \sqrt{(AA)^2 + (BB)^2 + (CC)^2}$$

or

$$DLTVG = \frac{(XL)(\sqrt{H})}{H} \qquad \text{(D-5)}$$

It is noted that "DLTVG" is computed only when the quantity (ZVPP(I)-ZVPPGI) is a positive number, i.e., when point "I" is in contact with the terrain. As such, "DLTVG" is the amount which point "I" penetrates the terrain in a direction normal to the terrain plane.

Velocity Vector of Vehicle-Point "I", Components Normal and Tangent to Terrain

Since the solution of equations for the model is performed in vehicle-fixed coordinates, the forces applied to the vehicle by the soil are computed in vehicle-fixed coordinates rather than space-fixed. Therefore $\overline{N}$ (vector normal to the terrain) must be converted accordingly.

$$\bar{N} = (AA)\bar{I} + (BB)\bar{J} + (CC)\bar{K} \qquad \text{(space-fixed)}$$

or

$$\bar{N} = (AV)\bar{i} + (BV)\bar{j} + (CV)\bar{k} \qquad \text{(vehicle-fixed)}$$

where $\bar{i}$, $\bar{j}$, and $\bar{k}$ are unit vectors parallel to X, Y, and Z, respectively (vehicle-fixed coordinate system).

By definition of AMTX (page 185 of Ref. 3),

$$\begin{Bmatrix} (AA) \\ (BB) \\ (CC) \end{Bmatrix} = \begin{bmatrix} & & \\ & \text{AMTX} & \\ & & \end{bmatrix} \begin{Bmatrix} (AV) \\ (BV) \\ (CV) \end{Bmatrix}$$

and by the property that $[\text{AMTX}]^{-1} = [\text{AMTX}]^T$,

$$\begin{Bmatrix} (AV) \\ (BV) \\ (CV) \end{Bmatrix} = \begin{bmatrix} & & \\ & \text{AMTX} & \\ & & \end{bmatrix}^T \begin{Bmatrix} (AA) \\ (BB) \\ (CC) \end{Bmatrix}$$

thus completely defining $\bar{N}$ in the vehicle-fixed coordinate system.

To define the velocity vector of point "I" on the vehicle the following known parameters are needed: U, V, and W which are the scalar components of linear velocity of the center of gravity of the vehicle taken along X, Y, and Z axes, respectively; and P, Q, and R which are scalar components of vehicle angular velocity taken about X, Y, and Z axes, respectively.

Let ($\overline{VCG} = U\bar{i} + V\bar{j} + W\bar{k}$) represent the linear velocity of the vehicle center of gravity, and ($\bar{\omega} = P\bar{i} + Q\bar{j} + R\bar{k}$) represent the angular velocity vector of the vehicle center of gravity and ($\bar{r} = XVP(I)\bar{i} + YVP(I)\bar{j} + ZVP(I)\bar{k}$) represent the radius vector from the vehicle center of gravity to the vehicle point "I".

Using the vectors $\overline{VCG}$, $\bar{\omega}$, and $\bar{r}$, the velocity vector of point "I" ($\overline{VI}$) is

$$\overline{VI} = \overline{VCG} + \bar{\omega} \times \bar{r} \quad .$$

and

$$\bar{\omega} \times \bar{r} = \begin{vmatrix} \bar{i} & \bar{j} & \bar{k} \\ P & Q & R \\ XVP(I) & YVP(I) & ZVP(I) \end{vmatrix}$$

or

$$\begin{aligned} \bar{\omega} \times \bar{r} = {} & (Q(ZVP(I)) - R(YVP(I)) \, \bar{i} \\ & - (P(ZVP(I)) - R(XVP(I)) \, \bar{j} \\ & + (P(YVP(I)) - Q(XVP(I))\bar{k} \end{aligned}$$

If $\overline{VI}$ is further defined as,

$$\overline{VI} = VUP\bar{i} + VVP\bar{j} + VWP\bar{k}$$

then

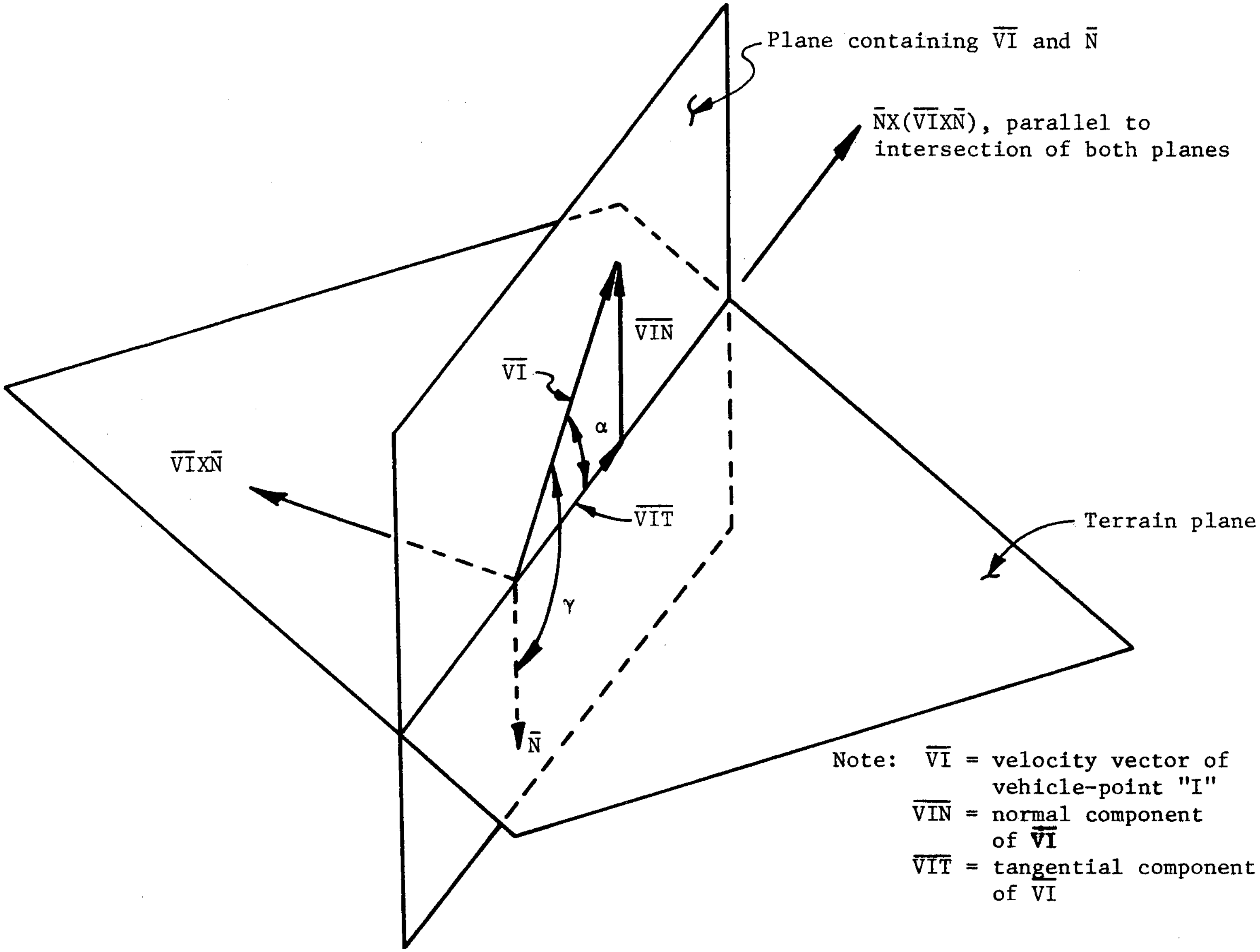
$$VUP = U + Q(ZVP(I)) - R(YVP(I))$$

$$VVP = V + R(XVP(I)) - P(ZVP(I))$$

$$VWP = W + P(YVP(I)) - Q(XVP(I))$$

At this point, with $\bar{N}$ and $\overline{VI}$ defined in the same coordinate system, $\overline{VI}$ can be resolved into two components one normal to the terrain plane and the other tangential to the terrain plane. Both of these components lie in a plane defined by and containing both $\bar{N}$ and $\overline{VI}$, as shown in Figure D-4. The vector normal to this plane is defined by

$$\overline{VI} \times \bar{N} = \begin{vmatrix} \bar{i} & \bar{j} & \bar{k} \\ VUP & VVP & VWP \\ AV & BV & CV \end{vmatrix}$$



Note: $\overline{VI}$ = velocity vector of vehicle-point "I"
$\overline{VIN}$ = normal component of $\overline{\mathbf{VI}}$
$\overline{VIT}$ = tangential component of $\overline{VI}$

Figure D-4. SCHEMATIC OF COMPONENTS NORMAL AND TANGENT TO TERRAIN OF VELOCITY VECTOR OF VEHICLE-POINT "I" or

$$\overline{VI} \times \bar{N} = (AVT)\bar{i} + (BVT)\bar{j} + (CVT)\bar{k}$$

where

$$AVT = (VVP)(CV) - (BV)(VWP)$$
$$BVT = (AV)(VWP) - (VUP)(CV)$$
$$CVT = (VUP)(BV) - (AV)(VVP) \quad .$$

The vector parallel to the intersection of the terrain plane with the plane containing $\overline{VI}$ and $\bar{N}$ (Figure D-4) is defined by

$$\bar{N} \times (\overline{VI} \times \bar{N}) = \begin{vmatrix} \bar{i} & \bar{j} & \bar{k} \\ AV & BV & CV \\ AVT & BVT & CVT \end{vmatrix}$$

or

$$\overline{XIV} = \bar{N} \times (\overline{VI} \times \bar{N}) = (AVNT)\bar{i} + (BVNT)\bar{j} + (CVNT)\bar{k}$$

where

$$AVNT = (BV)CVT) - (BVT)(CV)$$
$$BVNT = (AVT)(CV) - (AV)(CVT)$$
$$CVNT = (AV)(CVT) - (AVT)(CV) \quad .$$

The magnitude of the tangential component of $\overline{VI}$ is expressed by

$$VMPT = \left|\overline{VI}\right| \cdot \cos\alpha = VMP \cdot \cos\alpha$$

where

$$\mathrm{VMP} = \left|\overline{\mathrm{VI}}\right| = \sqrt{(\mathrm{VUP})^2 + (\mathrm{VVP})^2 + (\mathrm{VWP})^2} \qquad \text{(D-6)}$$

and

$$\cos\alpha = \frac{\overline{\mathrm{VI}} \cdot \overline{\mathrm{XIV}}}{\left|\overline{\mathrm{VI}}\right| \left|\overline{\mathrm{XIV}}\right|} \quad .$$

Also,

$$\mathrm{VNTIM} = \left|\overline{\mathrm{XIV}}\right| = \sqrt{(\mathrm{AVNT})^2 + (\mathrm{BVNT})^2 + (\mathrm{CVNT})^2}$$

and

$$\overline{\mathrm{VI}} \cdot \overline{\mathrm{XIV}} = (\mathrm{VUP})(\mathrm{AVNT}) + (\mathrm{VVP})(\mathrm{BVNT}) + (\mathrm{VWP})(\mathrm{CVNT}) \quad .$$

Then

$$\mathrm{VMPT} = \frac{(\mathrm{VUP})(\mathrm{AVNT}) + (\mathrm{VVP})(\mathrm{BVNT}) + (\mathrm{VWP})(\mathrm{CVNT})}{\mathrm{VNTIM}} \qquad \text{(D-7)}$$

The direction of the tangential component of $\overline{\mathrm{VI}}$ is the same as that of the unit vector $\overline{\mathrm{UXIV}}$, defined as

$$\overline{\mathrm{UXIV}} = \frac{\overline{\mathrm{XIV}}}{\mathrm{VNTIM}} = \frac{\overline{\mathrm{XIV}}}{\left|\overline{\mathrm{XIV}}\right|} \quad . \qquad \text{(D-8)}$$

Hence,

$$\overline{\mathrm{VIT}} = \frac{\mathrm{VMPT}(\overline{\mathrm{XIV}})}{\mathrm{VNTIM}} \quad . \qquad \text{(D-9)}$$

The magnitude of the normal component of $\overline{\mathrm{VI}}$ is expressed by

$$\mathrm{VELPN} = (\mathrm{VMP}) \cos\gamma$$

where,

$$\mathrm{VMP} = \left|\overline{\mathrm{VI}}\right| \text{ , (Equation (D-6)}$$

and

$$\cos \gamma = \frac{\overline{\mathrm{VI}} \cdot \bar{\mathrm{N}}}{\left|\overline{\mathrm{VI}}\right| \left|\bar{\mathrm{N}}\right|}$$

Also,

$$\mathrm{VNTM} = \left|\bar{\mathrm{N}}\right| = \sqrt{(\mathrm{AV})^2 + (\mathrm{BV})^2 \ (\mathrm{CV})^2}$$

and

$$\overline{\mathrm{VI}} \cdot \bar{\mathrm{N}} = (\mathrm{VUP})(\mathrm{AV}) + (\mathrm{VVP})(\mathrm{BV}) + (\mathrm{VWP})(\mathrm{CV}) \ .$$

Then,

$$\mathrm{VELPN} = \frac{(\mathrm{VUP})(\mathrm{AV}) + (\mathrm{VVP})(\mathrm{BV}) + (\mathrm{VWP})(\mathrm{CV})}{\mathrm{VNTM}} \qquad \text{(D-10)}$$

The direction of the normal component of $\overline{\mathrm{VI}}$ is the same as that of the unit vector $\overline{\mathrm{UN}}$, defined as

$$\overline{\mathrm{UN}} = \frac{\bar{\mathrm{N}}}{\left|\bar{\mathrm{N}}\right|} = \frac{\bar{\mathrm{N}}}{\mathrm{VNTM}} \ . \qquad \text{(D-11)}$$

Hence,

$$\overline{\mathrm{VIN}} = \frac{\mathrm{VELPN}(\bar{\mathrm{N}})}{\mathrm{VNTM}} \ . \qquad \text{(D-12)}$$

Using equations D-7 through D-12, the forces afforded by the soil to the vehicle are computed. The soil is modeled as a spring having a stiffness "SSTIFF" (lbs./in.) and a damper having a damping coefficient "XJ" (sec./in.), at the point of contact.

The force vector normal to the terrain is

$$\overline{FN} = -K(\overline{UN})$$

where $\overline{UN}$ is defined by Equation (D-11) and K = (SSTIFF)(DLTVG)(1.0 + (XJ)(VELPN)). (Note DLTVG is defined in equation (D-5). For convenience, re-define $\overline{FN}$ as,

$$\overline{FN} = FNTX\bar{i} + FNTY\bar{j} + FNTZ\bar{k}$$

where

$$\left.\begin{aligned} FNTX &= \frac{-K(AV)}{VNTM} \\ FNTY &= \frac{-K(BV)}{VNTM} \\ FNTZ &= \frac{-K(CV)}{VNTM} \end{aligned}\right\} . \qquad (D-13)$$

The force vector tangential to the terrain (friction force) is

$$\overline{FT} = -(KK)(\overline{UXIV})$$

where $\overline{UXIV}$ is defined by equation (D-8) and,

$$KK = (SSTIFF)(DLTVG)(FRFAC)$$

Note: FRFAC = Friction factor between vehicle and terrain

For convenience, re-define $\overline{FT}$ as,

$$\overline{FT} = FRFCX\bar{i} + FRFCY\bar{j} + FRFCZ\bar{k}$$

where

$$\left.\begin{aligned} FRFCX &= \frac{-(KK)(AVNT)}{VNTIM} \\ FRFCY &= \frac{-(KK)(BVNT)}{VNTIM} \\ FRFCZ &= \frac{-(KK)(CVNT)}{VNTIM} \end{aligned}\right\} . \qquad (D\text{-}14)$$

The resulting force vector on vehicle-point "I" when terrain contact occurs can be expressed as

$$\overline{FRES} = \overline{FN} + \overline{FT} = (FXVG)\bar{i} + (FYVG)\bar{j} + (FZVG)\bar{k}$$

where

$$\left.\begin{aligned} FXVG &= FNTX + FRFCX \\ FYVG &= FNTY + FRFCY \\ FZVG &= FNTZ + FRFCZ \end{aligned}\right\} \qquad (D\text{-}15)$$

Since the mass of the vehicle-structure is concentrated at a point (the center of gravity), it is necessary that any force applied to the vehicle-structure be transferred to that point. This transfer is accomplished by applying the forces defined in equations (D-15) plus an additional moment vector defined as

$$\overline{XMV} = \bar{r} \times \overline{FRES}$$

where

$$\bar{r} = (XVP(I))\bar{i} + (YVP(I))\bar{j} + (ZVP(I))\bar{k} \quad .$$

$$\overline{XMV} = \begin{vmatrix} \bar{i} & \bar{j} & \bar{k} \\ XVP(I) & YVP(I) & ZVP(I) \\ FXVG & FYVG & FZVG \end{vmatrix}$$

If $\overline{XMV}$ is re-defined as

$$\overline{XMV} = (XMVGX)\bar{i} + (XMVGY)\bar{j} + (XMVGZ)\bar{k}$$

then,

$$\left.\begin{aligned} XMVGX &= (YVP(I)(FZVG) - (FYVG)(ZVP(I)) \\ XMVGY &= (FXVG)(ZVP(I)) - (XVP(I))(FZVG) \\ XMVGZ &= (XVP(I))(FYVG) - (FXVG)(YVP(I)) \end{aligned}\right\} \qquad (D\text{-}16)$$

Therefore, in summary, the forces and moments defined by equations (D-15) and (D-16) are applied to the center of gravity of the vehicle when contact occurs between some point on the vehicle-structure and the terrain.