

**COMPUTER MODEL TO SIMULATE TRUCK ACCIDENTS
ON EXIT RAMPS**

by

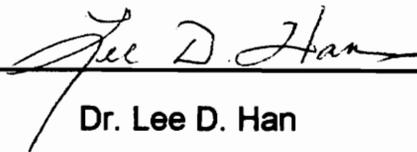
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**Thesis submitted to the Faculty of the
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in partial fulfillment of the requirements for the degree of
Master of Science
in
Civil Engineering**

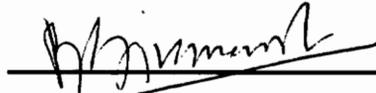
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(ABSTRACT)

Though the trucks consist of only 3% of the total registered vehicles in the United States, truck accidents have been a major concern due to the property damage and loss of lives involved. Growth trends show that the truck travel will reach 1 trillion vehicle miles by the end of the year 2000. This increase in truck travel poses a major threat to the safety of both passenger cars and trucks. To improve the safety of the trucks as well as the passenger cars, understanding of the factors affecting the truck safety is essential. Models developed in the past were mostly regression models which tried to relate the truck accidents to the geometry of the highways. But most of these models did not consider all the factors affecting the safety of the trucks. Simulation models were developed in the past to study the dynamic vehicle response to different highway geometry especially, on exit ramps where most of the rollover accidents occur every year. But not enough research was done in the past on the weather and surface conditions affecting the truck safety.

The objective of this study is to develop a graphics based computer simulation model to test the trucks for different geometric features, surface conditions and

truck characteristics on exit ramps and to gain a better understanding of the factors affecting the safety of the trucks.

A high level simulation language SIMSCRIPTII.5 was used in the study to develop a simulation model. To make the model is to understand, graphical windows and animation were included in the model. Three exit ramps were tested in this model. Two these ramps are existing ramps in southwestern Virginia and they had rollover accidents reported on them in the past. The parameters and other surface and geometric conditions can be changed any time during the simulation. The model indicated that deceleration lengths provided may not be sufficient for heavy trucks traveling at higher speeds to reduce their speeds to the safe speed limits on the ramps. The posted speed limits may not be suitable for heavy trucks especially when the surface is not dry. The model also indicated that the tractor-semitrailers are more exposed to rollovers than any other type of trucks.

*To
Annie
Ramesh &
beloved Chinni*

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1.0 INTRODUCTION

1.1 Background of the Problem

Stepping into the decade of 1990's, it is obvious that the economy of united states largely based on freight transportation. Ninety percent of this freight movement takes place through the highways by means of truck. Vehicle transportation growth trend indicates that the truck travel has increased by 50% over the past decade. Based on this trend, it is estimated that by the year 2000, truck travel will exceed 1 trillion miles per year. This increase in truck travel has caused substantial in the number of highway accidents involving large and medium trucks. According to NHTSA report [24] there were 3,49,000 truck accidents of all severities in the year of 1989 resulting 5,491 deaths and 12,400 injuries. Rough estimates show that 500 million to 1 billion dollars of property damage was resulted from these accidents. Trucks, both single and combined accounted for only 3% of all the registered vehicles but for the 7% of all the vehicle miles traveled. This increasing trend of truck traveling will cause operational and safety problems for both trucks and passenger vehicles. From safety and economical point of view, truck accidents, though less in number compared to the non-truck accidents, are more serious in nature and involve more property damage.

Studies have examined the critical features affecting the truck accidents. Major factors affecting the safety of the trucks are concluded to be geometric features

of the highway and environmental conditions or the combination of above two. All the statistics in this report are collected from the NHTSA 1989 accident summary [24] and from the Virginia Department Of Transportation (VDOT) [28].

1.1.1 National Problem

Though the trucks accounted for only 3 percent of all the registered vehicles, they traveled 7 percent of the total vehicle miles in 1989 in the United States. Average combination truck traveled about 60,000 miles compared to average passenger vehicle's 10,000 miles. Traveling so many miles per vehicle, trucks are more often exposed to the possibility of being involved in crashes. Trucks represented 8% of the vehicles involved in fatal accidents, 2 percent of those involved in injury crashes and 3 percent of those in property-damage-only crashes in the year 1989. Five percent of truck crashes, but only two percent of passenger vehicle crashes that resulted in injury were fatal crashes. Over the past ten years, combination trucks have been involved in an average of 3,823 fatal crashes per year, single unit trucks in an average of 1,103 crashes and passenger vehicles in an average of 36,796 crashes per year. Data shows that number of fatal crashes per year for the passenger vehicles reduced considerably but, the number of fatal accidents involving trucks remained fairly constant in the past decade. Fatal crashes rate is highest for the combination trucks and lowest for the passenger vehicles.

Due to these truck accidents there have been 4 to 5 thousand deaths every year and property worth more than a billion is lost in the United States., because of the large mass of the truck, though the truck occupants are prevented from being involved in a serious injury, passengers of the other vehicle involved in the accident are exposed to very serious injuries. Hence, truck accidents in United

States have more impact on the passenger vehicles than on their own selves. In the year 1989, 75 percent of all the persons killed and 73 percent of all the persons injured were the occupants of the other vehicles in collision. Pedestrians and cyclists accounted for 8 percent of the fatalities. Though most of the truck accidents took place when no adverse atmospheric conditions prevailed, accidents occurred in unfavorable weather conditions have considerable importance because of their severe nature. About 6 to 7 percent of the total truck accidents are due to jackknifing of the trucks.

The following tables show the detailed data of truck accidents in United States during the year 1989.[24]

Registered Vehicles	Total	Percent
Trucks:		
Single Unit	4,102,863	2
Combination	1,589,285	1
Passenger Vehicles	180,943,359	94
All other Vehicles	5,058,955	3
Total Registered Vehicles	191,694,462	100
Annual Vehicle Miles of Travel	Total (in millions)	Average (per vehicle)
Trucks:		
Single Unit	53,190	12,964
Combination	95,567	60,132
Passenger Vehicles	1,942,173	10,734
All other Vehicles	16,110	3,184
Total Vehicle miles of travel	2,107,040	10,992

Table 1.1.1.1: Motor vehicle statistics, 1989

	Fatal	Percent	Injury	percent	P.D. only	percent
Crashes Involving:						
Trucks	4,675	11	87,000	4	245,000	5
Passenger Vehicles	37,104	91	1,986,500	95	4,183,000	93
All Other Vehicles	4,595	11	248,500	12	616,000	4
All Crashes	40,741	--	2,092,000	--	4,509,000	--
Vehicles Involved						
Trucks	4,985	8	90,500	2	254,000	3
Passenger Vehicles	51,112	84	3,357,000	90	6,880,500	88
All Other Vehicles	4,773	8	265,000	7	646,500	8
All Vehicles	60,870	100	3,712,500	100	7,781,000	100

Table 1.1.1.2: Crashes and vehicles involved by type and severity [24]

1.1.2 Local Problem in Southwest Virginia

In the state of Virginia, which consists interstate mileage of 1061.4 miles, there were a total of 12,038 accidents in the year 1989, causing 124 deaths, 6874 injuries and property damage worth of 54 million dollars. Out of these 12,038 accidents, 2,188 were the ones involving trucks which is about 20 percent. In a period of 5 years between 1986-1990, 64,367 crashes involving trucks were reported in Virginia causing 811 deaths and 21,439 injuries Truck accidents have been a major concern in Virginia because of its high percentage compared to the tuck accidents in the U.S. Out of all the 811 deaths only 148 of them were truck occupants which shows that truck crashes are causing more damage to the people traveling in passenger vehicles. Statistics of truck accidents on Virginia highways show that 1 person is killed for every 79.4 crashes and 1 occupant is killed in every 434.9 crashes, one interstate rollover is reported in every 117.9 crashes and one ramp rollover is reported in every 545.5 crashes. Between 1986 and 1990, there have been 399 rollover accidents involving trucks. Out of these 399, 145 were reported on Interstate 81, which is about 36 percent. In 1989, out of 2,188 total truck accidents, only 73 were rollover accidents which is

about 4 percent. In contrast to this, in a period of 3 years between 1987-89 out of a total 258 accidents reported on I-81, 89 of them were rollover accidents which is about 35 percent. This shows that the rollover, which is mainly caused by insufficient geometric features or unfavorable weather conditions or the combination of the above two, has been a major problem on I-81. Though most of the crashes were reported during day time and on dry surface conditions, 93 out of 258 (36%) accidents were reported when the surface was not dry, compared to the 22 percent of accidents which were reported in unfavorable atmospheric conditions in the whole United States.

Hence the environment, in the form of snow rain ice fog etc., has a major effect on the truck crashes on I-81. Total property damages in the last 3 years on I-81 were about 2.5 million dollars and the total number of persons killed were two. Major factors affecting these accidents in the last 3 years were driver inattention (123), road slick (46), speeding (11), vehicle defect (17), and alcohol (8). In all the trucks involved in these accidents on I-81, 20% of them were straight trucks 79% of them were tractor trailers and one percent of them were double trucks.

Following table show the detailed accident data on I-81 and on all other interstate highways in Virginia.

Year	1987	1988	1989	Total
Fatal Accidents	1	1	0	2
Injury Accidents	35	29	34	98
Property Damage accidents	64	48	46	158
Non-Injury pedestrian accidents	0	0	0	0
Sub Total	100	78	80	258

Table 1.1.2.1: Truck accidents by severity on I-81[28]

Surface Condition	1987	1988	1989	Total
Dry	71	53	41	165
Wet	9	19	17	45
Snowy	17	3	12	32
Icy	3	3	10	16
Muddy	0	0	0	0
Oily	0	0	0	0
Other	0	0	0	0
Total	100	78	80	258

Table 1.1.2.2: Truck accidents by surface condition on I-81[28]

Weather Condition	No. of Accidents
Clear	122
Cloudy	54
Fog	4
Mist	4
Raining	35
Snowing	32
Sleeting	6
Smoke - Dust	0
Not Stated	1
Other	0
Total	258

Table 1.1.2.3: Truck accidents by weather conditions [28]

In order to find the causes for the large no. of truck accidents, a clear understanding of truck with other vehicles and geometry of the highway is required. Though a number of models were developed in the past, they could not explain the truck accidents very clearly. The main objective of this study is develop a computer simulation model to test the trucks for different highway and truck characteristics.

1.2 Research Objectives

The objectives of this research are:

- To study highway design practices and geometric features of the highways affecting the safety of the trucks
- To study truck accident characteristics, and
- To develop a simulation model to test the trucks for different conditions

1.3 Summary of The Other Chapters

A brief introduction of the national and local problems and the objectives of the study are discussed in this chapter. The second chapter deals with the literature review conducted as a part of this research on truck and highway characteristics affecting the truck safety some of the past models were also discussed in this chapter. In the third chapter, the methodology used in developing the model is discussed and also the basics of simulation and SIMSCRIPTII.5 structure are discussed in this chapter. The simulation model is described in the fourth chapter along with the computer program and and chapter 5 deals with the model validation and Results are discussed in chapter 6 and the last chapter, chapter7 concludes the research with some recommendations.

2.0 LITERATURE REVIEW

The main objective of the literature review is to obtain sufficient knowledge of the past research done on different variables such as truck characteristics and road features affecting the safety of trucks. As the main objective of this research is to develop a simulation model relating geometric features of the roadway, the changing surface conditions due to the changes in weather and the truck characteristics like weight, payload height etc., the literature review has mainly been concentrated in the following areas.

- Geometric features of the roadway affecting the truck safety.
- Truck characteristics and rollover dynamics of heavy trucks.
- Surface conditions and the changes in the value of side friction factor.

Literature review done on the geometric features of the highways and, ramps in general revealed that most of the existing highways were designed and built according to the AASHTO green book, Geometric Design of Highways, 1984. The 1984 edition of the green book considers mainly passenger cars and does not provide enough safety factors for the heavy trucks. Though the latest 1990 edition of the book provides some provisions for heavy trucks, it does not accommodate for the increase of the sizes of heavy trucks from time to time. As our major concern is about the trucks exiting from interstate ramps with excessive speeds, geometric aspects of the interstate ramps are given careful consideration.

Though the main emphasis is on the ramp geometric features, overall highway geometric features were given enough consideration to obtain good insight of nature of the truck accidents. A review of current operational and design criteria identified the following criteria based on vehicle characteristics.

- Stopping sight distance
- Passing and no-passing zones on two lane highways
- Decision sight distance
- Intersection sight distance
- Intersection and channelization geometric features
- Railroad-highway grade crossing sight distance
- Crest vertical curve length
- Sag vertical curve length
- Critical length of grade
- Lane width
- Horizontal curve radius and superelevation
- Pavement widening on horizontal curves
- Cross-slope breaks
- Roadside slopes
- Vehicle change interval
- Sign placement

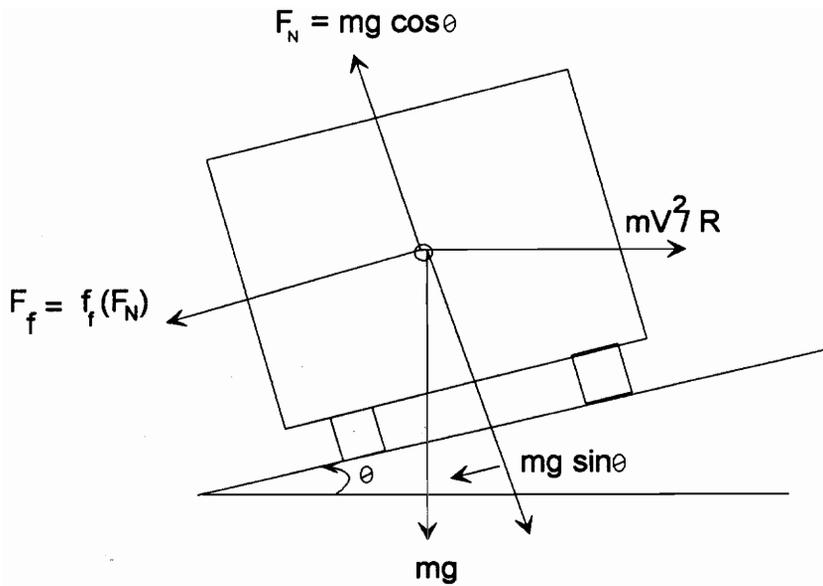
Truck accidents differ very much from the passenger car accidents because trucks differ from passenger cars in a number of aspects which are outlined below [19]:

1. Trucks are longer, wider, heavier, less maneuverable, and require greater stopping distances than passenger cars or other vehicle types. Thus, trucks are often more critical in highway design and operation than other vehicles.
2. Trucks have poorer acceleration and deceleration capabilities.
3. Many current highway design and operational standards are based on passenger car characteristics, even though truck characteristics may be more critical.
4. Average truck is about 2 years older than the average car, with the result that new vehicle design standards require more time for implementation in the truck population.
5. Trucks have been increasing as a percentage of the traffic stream. On some interstate freeways, they constitute 20 to 30 percent of the traffic.
6. The property damage is higher for accidents involving truck than that involving passenger cars.

Due to the above differences, truck accidents are more severe and should be given special consideration.

2.1 Geometry of the Roadway Affecting the Truck Safety

The major elements any ramp design are superelevation and its development, side friction, acceleration and deceleration lanes, radius of the horizontal curve and the degree of curvature. The basic idea of introducing a superelevation is for counteracting the centrifugal force acting on the vehicle negotiating a curved path. Figure 2.1.1 shows the derivation of relation between three basic elements of the ramp design to the speed of the vehicle.



$$\frac{mV^2}{R} = mg \sin \theta + f_f(F_N) \quad \dots(2.1.1)$$

$$\frac{mV^2}{R} = mg \sin \theta + f_f mg \cos \theta \quad \dots(2.1.2)$$

deviding through by g (cos θ) yields

$$\frac{V^2}{Rg (\cos \theta)} = \tan \theta + f_f : \theta, \text{ small angle assumption}$$

$$\frac{V^2}{Rg} = e + f \quad \dots(2.1.3)$$

$$\frac{V^2}{15 R} = e + f \quad \dots(2.1.4)$$

where e , superelevation ft / ft

f , friction factor

V , velocity mi / hr

R , radius of curve in ft

Figure 2.2.1: Derivation of minimum radius equation

A major work concerning the relationship between accidents and the geometric and traffic characteristics at interchanges is the 1969 study published by the Bureau of Public Roads [6]. Although this is based on data obtained from 1959 to 1965, the bulk of the Interstate system had been constructed and a large and a variety of interchanges from about 20 states were represented. In this study, accident counts and accident rates were determined for interchanges of various types (full cloverleaf, diamond, etc.), and multiple linear regression models were developed to permit estimation of accident rates as a function of such variables as ADT, geometric features, and the proportion of commercial vehicles in the traffic stream. Fisher [15], in reviewing four years of accident records on interchanges which included a number of older facilities, stated that higher design standards simply reduced the total no. of accidents but that the same type of accidents occurred at all interchanges. Browner [3], correlated mass accident data with design variables at individual interchange sites. He conducted an extreme analysis isolating sites having an unusually large number of accidents per year relative to the other sites of the same type were studied in closer detail.

A more recent study done by the University of Michigan Transportation Research Institute (UMTRI) [2] reported the following deficiencies in the geometry of most of the existing highway ramps.

1. Poor transition to superelevation
2. Abrupt changes in compound curves
3. Short deceleration lanes on the tight-radius
4. Steep down grade at the exit ramp
5. Provision of curb on the outside of entrance ramp

6. A low friction factor

And the study concluded that truck loss of control accidents on interchange ramps are predominantly rollover events. The relatively clean character of the road side on high-design highways results in rather few collisions with fixed objects off-road. Run-off-the road accidents, which happen because of the vertical grade, most often result in rollovers.

Rollover accidents are precipitated at sites having high levels of side friction demand, particularly due to the deficiencies mentioned above. The AASHTO policy for the geometric design of curves provides for virtually no margin of safety against rollover for certain trucks. This deficiency in the design policy is so startling that one can only assume that the highway engineering community has simply not had data available showing the very low stability limits of commercial vehicles. The AASHTO policy for the length of deceleration lanes does not provide for the deceleration of truck combinations in a manner analogous to the treatment for passenger cars. The tremendous mismatch between the provided lengths of acceleration lanes and the acceleration length demands of loaded trucks may be prompting the truck driver to speed in the later portions of the many interchange ramps in order to mitigate the inevitable conflicts associated with merging. Another concern is the AASHTO policy of accepting ramp down grades as high as 8 percent, this may be ill advised at sites on which a relatively sharp curve remains to be negotiated toward the bottom of the grade.

Another study done by Harwood et al [20], at Midwest Research Institute has concluded that the current AASHTO criteria for horizontal curve radius and

superelevation at particular design speeds are adequate to accommodate trucks. The existing criteria provide margins of safety against skidding off the road and against rollover that are substantially lower for trucks than for passenger cars. However, the existing AASHTO criteria provide an adequate margin of safety for a truck if the truck is traveling at the design speed. The study also revealed that the current superelevation transition methods appear adequate to accommodate trucks and the use of spiral transition is preferable to the traditional 2/3 - 1/3 rule. But the resulting reduction in maximum lateral acceleration is typically only about 0.01g.

2.2 Truck Characteristics and Rollover Dynamics of Heavy Trucks

As the study involves developing a model which relates truck accidents to truck characteristics along with the roadway features, it is essential that a thorough review be done on these issues. After reviewing the past research on the truck characteristics and payload height effects on the stability of the heavy trucks, it can be concluded that the height and the distribution of the payload play a major role in deciding the stability of the trucks traveling on exit ramps. A complete review of many truck characteristics can be found in National Highway Traffic Safety Administration (NHTSA) report "Heavy Truck Safety Study" [7] and another NHTSA report, "A Factbook of Mechanical Properties of the Components for Single-Unit and Articulated Heavy Trucks" [12] provides detailed available data on the ranges of specific truck characteristics. The AASHTO green book [1] includes ten design vehicles for use in highway design: a passenger car, two buses, four trucks and three recreational vehicles. The design vehicles are used as the basis for design criteria for which vehicle length,

width, height, or off tracking are controlling factors. Table 2.2.1 shows the dimensions for the ten design vehicles.

Dimension (ft)												
Design Vehicle Type	Symbol	Overall			Overhang							
		Height	width	Length	Front	Rear	WB1	WB2	S	T	WB 1	
Passenger Car	P	4.25	7	19	3	5	11					
Single Unit Truck	SU	13.5	8.5	30	4	6	20					
Single Unit Bus	BUS	13.5	8.5	40	7	8	25					
Articulated Bus	A-BUS	10.5	8.5	60	8.5	9.5	18		4	20		
Comb. Trucks												
Inter. Semitrailer	WB-40	13.5	8.5	50	4	6	13	27				
Large Semitrailer	WB-50	13.5	8.5	55	3	2	20	30				
Double Bottom ST	WB-60	13.5	8.5	65	2	3	9.7	20	4	5.4	20.9	
Recr. Vehicles												
Motor Home	MH		8	30	4	6	20					
Car and Camper	P/T		8	49	3	10	11	5	18			
Car and Boat	P/B		8	42	3	8	11	5	15			

Table 2.2.1: AASHTO design vehicle dimensions

The four design trucks specified by AASHTO include a single-unit truck (SU), an intermediate semi-trailer truck (WB-40), a large semi-trailer truck (WB-40), and a double bottom semi-trailer-full trailer truck (WB-60). Longer combination vehicles (LCVs), including rocky mountain doubles, turnpike doubles, and triples, are permitted to operate only in a few states. The specific dimensions of these vehicles have been tabulated in the FHWA LCV study [14].

Many studies done in the past and in particular, the one by Harwood et al [20] identified the following as the major truck characteristics affecting the design of the highways and ramps:

1. Braking Efficiency

Current truck braking systems are limited in their ability to take advantage of all of the friction available at the tire-pavement interface. Fancher [13] has estimated that braking efficiency for single unit truck is between 55 and 59 percent of peak available friction. Both Fancher and NCHRP report 270 [17]

assume that this same level of braking efficiency is applicable to tractor-trailer trucks. A primary reason for this relatively low level of braking efficiency is that most controlled braking takes place at a value of percent slip less than level which produces the peak braking friction coefficient.

2. Truck Acceleration Characteristics

Truck acceleration performance can be divided into two aspects namely, low speed and high speed acceleration. The low speed acceleration ability of a truck determines the time required for it to clear a relatively short hazard zone such as an intersection or railroad-highway grade crossing. The primary factors that affect the clearance timings are length of hazard zone, length of truck, truck weight to power ratio, truck gear ratio and roadway geometry.

Though it might need a fairly complex to represent above variables, a simplified analytical model of the low speed acceleration of trucks has been developed by Gillespie [17]. The Gillespie model estimates the time required for a truck to clear a hazard zone, starting from a full stop, as:

$$t_c = (0.682(L_{HZ} + L_T)/(V_{mg})) + 3.0 \quad \dots 2.2.2.1$$

where t_c = time required to clear hazard zone

L_{HZ} = length of hazard zone

L_T = length of truck

V_{mg} = maximum speed in the gear selected by driver (mi/h)

on a level road V_{mg} can be calculated as $V_{mg} = 60/gr$...2.2.2.2

gr = gear ratio selected by the driver

3. Pavement and Truck characteristics Affecting Braking Distance

Highway agencies generally measure pavement friction by means of locked wheel skid tests with a standard tire. The results of these tests are multiplied by 100 and referred to as skid numbers rather than coefficients of friction. Although they are usually determined at 40 mph, a procedure is available to determine the skid number at any speed from the skid number at 40 mph [13]. The peak coefficient of friction (f_p) can be estimated from the sliding coefficient of friction by the following relationship [13].

$$f_p = 1.45 f_s \quad \dots 2.2.3.1$$

The above equation represents the average relationship for truck tires between peak and sliding friction. Estimates of a braking distance in a recent evaluation of stopping sight distance requirements in NCHRP report 270 used an assumed pavement skid number at 40 mph (SN_{40}) of 28. The AASHTO green book [1] criteria for stopping sight distance are based on a pavement with SN_{40} equal to 32.

Literature review done on tire properties reveals that truck tires are designed primarily for wear resistance. For this reason they tend to have some what lower wet friction coefficients than passenger car tires. It is generally estimated that truck tires have coefficients of friction that are about 70 percent of those of passenger car tires [13]. However, passenger car tires generally have coefficient of friction that are about 120 percent of the friction coefficients of the standard tires used in skid testing. Thus, the peak coefficient of friction can be estimated from skid test results with the following relation ship:

$$f_p = (1.20)(0.70)(1.45)f_s = 0.0122 SN_{40} \quad \dots 2.2.3.2$$

The NCHRP report 270 [13] estimated the reduction in friction coefficient of tires as their depth decreases, using the following equation.

$$TF = 1 - \Delta f_p (1 - \sqrt{(x / n)}) / (f_p) \quad \dots 2.2.3.3$$

where, TF = adjustment factor for tire tread depth
 Δf_p = difference in coefficient of friction between new and bald tires
 x = remaining tread depth
 n = minimum tread depth with coefficient of friction equivalent to a new tire

4. Rolling Resistance

The rolling resistance of tires, F_r , is defined as the ratio of power lost due to rolling resistance to speed. F_r can be estimated using the following SAE equations:

$$F_r = 0.001 (4.1 + 0.041 V) \text{ for radial tires} \quad \dots 2.2.4.1$$

$$F_r = 0.001 (5.3 + 0.044 V) \text{ for mixed vehicles} \quad \dots 2.2.4.2$$

$$F_r = 0.001 (6.6 + 0.046 V) \text{ for bias-ply tires} \quad \dots 2.2.4.3$$

where V is the speed in mph.

5. Aerodynamic Drag

The aerodynamic drag force is estimated by the following relationship [21].

$$F_a = 1.1D C_D A V^2$$

...2.2.5.1

where, F_a = aerodynamic drag (lb)

D = air density

C_D = drag coefficient

A = truck frontal area (ft X ft)

V = truck speed (mph)

2.2.1 Suspension Characteristics

The review is primarily based on a summary of suspension characteristics from the NHTSA factbook of truck characteristics [12] and on some other references. The literature review of the past studies concluded the following.

The suspension of a heavy vehicle affects its dynamic responses in three major ways:

- Determining dynamic loads on tires
- Orienting the tires under dynamic loads
- Controlling vehicle body motions with respect to the axles

Suspension characteristics can be categorized by the following basic mechanical properties:

1. Vertical stiffness

The vertical stiffness of truck is mainly determined by the spring elements. Generally these element are either leaf springs or air springs.

The vertical loads on the trailer of a loaded truck can be up to four times greater than when the tractor is unloaded [9]. Since the load on the suspension can vary greatly, the springs must be very stiff for a fully loaded truck and much less stiff for an unloaded truck. Air springs are particularly well suited for such a range of loadings. With leaf springs the stiffness can also change under different loadings, but not quite as much as the air suspension. Vertical stiffness is extremely important in ride quality, and it also has some effect on vehicle dynamics. The range of vertical stiffness per axle is given below in table 2.2.1.1.

Type of Suspension	Range of Vertical Stiffness (lb/in)
Front Suspension	2,000 - 2,750
Air Suspension	1,000 - 7,000
Four-Spring	8,000 - 21,000
Walking Beam	10,000 - 21,000
Single-Axle Leaf Spring	8,500 - 13,750

Table 2.2.1.1: Typical range of vertical stiffnesses [12]

2. Damping

Damping is a function of mean load and displacement. Damping has a moderate effect on rearward amplification and the transient dynamic behavior of the vehicle. A lack of damping can create a system that is likely to oscillate and produce large dynamic loads on the axles. Damping is set so that a maximum ride quality can be achieved. Increased damping usually reduces rearward amplification of steering inputs in multi-trailer combination trucks and can, thus, increase the stability in emergency maneuvers. A typical range of values for damping is given in table 2.2.1.2.

Type of Suspension	Range of Damping (lb)
Front Suspension	800 - 1,250
Air Suspension	550 - 1,200
Four-Spring	1,200 - 2,700
Walking Beam	700 - 2,000
Single-Axle Leaf Spring	1,800 - 2,400

Table 2.2.1.2: Typical range of damping for trucks [12].

3. Static Load Equalization

Good load equalization is important for a truck traveling over a bumpy road, when the frame of the truck is being pitched. Tandem axle suspensions such as walking-beam and four-spring suspensions are typically made symmetrical to distribute the load evenly. Typically, most tandem axles are very good at evenly distributing the weight on a tandem axle. Static measurements on tandem axles have shown that the largest variation is on the order of about 5 percent more weight on one axle than the other one.

4. Height of Roll center

When truck rolls or tilts sideways, it tends to roll about a specific point, called the roll center. The roll center is located at the line of action where the lateral forces interact between the chassis and the suspension. With a four-spring suspension, the leaf spring will determine the roll center location. Roll center heights are measured from the ground. Typical values are given in the table 2.2.1.3 below

Type of Suspension	Range of Roll Center Height (in)
Front Suspension	18.5 - 20
Air Suspension	24 - 29.5
Four-Spring	23 - 31
Walking Beam	21.5 - 23
Single-Axle Leaf Spring	25 - 28

Table 2.2.1.3: Typical range of roll center heights for truck suspensions [12].

5. Roll stiffness

Roll stiffness is a measure of a suspension system's resistance to rolling. As a truck rolls, the vertical springs deform to cause a resisting moment. This moment is dependent on the vertical spring constants and lateral spacing of the springs. The steel leaf springs provide roll resistance without using any extra mechanism for increased roll resistance. Air-spring suspensions generally need some auxiliary mechanism to provide adequate roll resistance. Most air spring systems use the axle housing to assist in roll resistance. This is done by rigidly clamping the axle housing to the trailing arms. Very high roll stiffness can be achieved with this approach.

The height of the roll center plays an important role in the rolling tendency of a vehicle. As a truck goes around a horizontal curve, the centrifugal force causes the truck body to roll about its roll center. This will also cause the center of gravity to produce a moment about roll center, due to its shift in position. The higher the roll center, the shorter the moment arm and the smaller the moment that is produced.

A typical range of roll stiffnesses on a per axle basis is given in table 2.2.1.4.

Type of Suspension	Range of Rollover Stiffnesses (in-lb/ deg)
Front Suspension	0.017 - 0.025
Air Suspension	0.025 - 0.09
Four-Spring	0.065 - 0.140
Walking Beam	0.07 - 0.16
Single-Axle Leaf Spring	0.052 - 0.089

Table 2.2.1.4: Typical range of roll stiffness for truck suspensions

6. Roll steer coefficient

Non-steering axles can deflect slightly to create a steering effect as a result of vehicle roll. As the truck body rolls, one side of the axle moves forward while the other side moves aft. This unintentional steering is created by the suspension and tire forces. The tendency to steer in a roll is measured with respect to the amount of vehicle roll present. This steering can greatly affect truck handling, particularly in a turn. The units used in measuring the roll steer coefficient are degrees of steer per degree of roll. A positive roll steer coefficient means that the axle will steer toward the outside of the turn and a negative coefficient means that the axle will steer toward the inside of the turn. A typical range of values is given in table 2.2.1.5 below.

Type of Suspension	Range of Roll Steer Coefficient(deg/deg)
Air Suspension	0.01 - 0.23
Four-Spring	-0.04 - 0.23
Walking Beam	0.16 - 0.21
Single-Axle Leaf Spring	0.0 - 0.07

Table 2.2.1.5: Typical range of roll steer coefficients for truck suspensions [12]

7. Compliance Steer Coefficient

Compliance steering is very similar to roll steering, except that it is caused by brake forces, side forces and aligning moments. These forces and moments cause deflections of rubber bushings and other links, which in turn cause the steering effect. Compliance steering is not very large for non-steering axles. A typical range of values is given in table 2.2.1.6.

Type of Suspension	Range of Compliance Steering (deg/in-lb)/10 ⁶
Air Suspension	3.8 - 6.0
Four-Spring	3.7 - 7.25
Walking Beam	6.25 - 10.0
Single-Axle Leaf Spring	4.9 - 5.4

Table 2.2.1.6: Typical range of compliance steer coefficients for truck suspensions

2.2.2 Rollover Threshold

A vehicles resistance to rollover is measured by the maximum lateral acceleration that can be achieved without causing rollover. Figure 2.2.2.1 shows the graphical representation of rollover threshold of a tractor semi-trailer. Considerable research was done in the past to estimate the rollover threshold values for different trucks and for different loading configurations. A research done by H.W. McGhee [22] revealed that passenger cars have rollover thresholds of about 1.20g. The typical passenger car tracking a horizontal curve or making a turn at too high a speed is likely to skid off the road due to inadequate tire-pavement friction long before its rollover threshold is reached. Trucks, on the other hand, generally have rollover thresholds that are less than

the available tire-pavement friction on dry pavements. Thus, rollovers are much more likely as a failure mode for trucks than passenger cars.

Truck rollovers are caused by high lateral acceleration in a turning maneuver. As lateral acceleration increases, the wheels on the inside of the turn begin to lift off the pavement. Generally, due to uneven load distribution and to uneven suspension, tire, and structural stiffness, all of the wheels will not begin to lift off the pavement at the same time. It is possible for one wheel of a truck to lift off the pavement without producing a rollover; however, this creates a very unstable situation that could ultimately lead to rollover.

Figure 2.2.2.2 summarizes the threshold of lateral acceleration calculated for accidents in British Columbia (B.C) reported in the paper by Navin [25] and some reported by Ervin (1983) [8]. The average B.C. rollover acceleration is 0.46 which corresponds well with the United States value of .47g. These low normal accelerations are roughly sustained by a typical sedan in yaw maneuver. A significant research was done in the past on truck rollover thresholds by Ervin et al [2,8,9] at UMTRI.

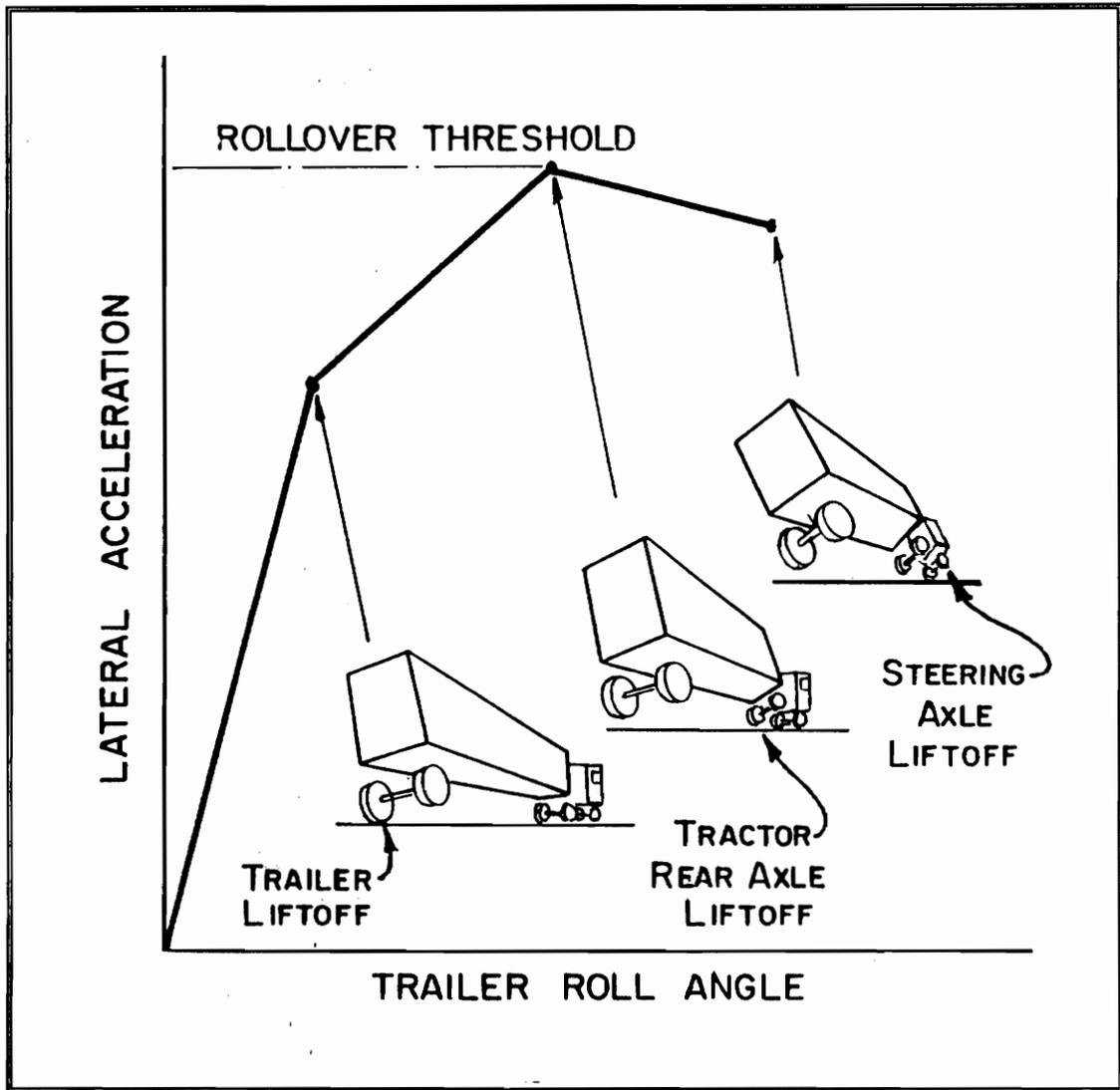


Figure 2.2.2.1: Typical axle lift-off sequence on figure defining rollover threshold [9]

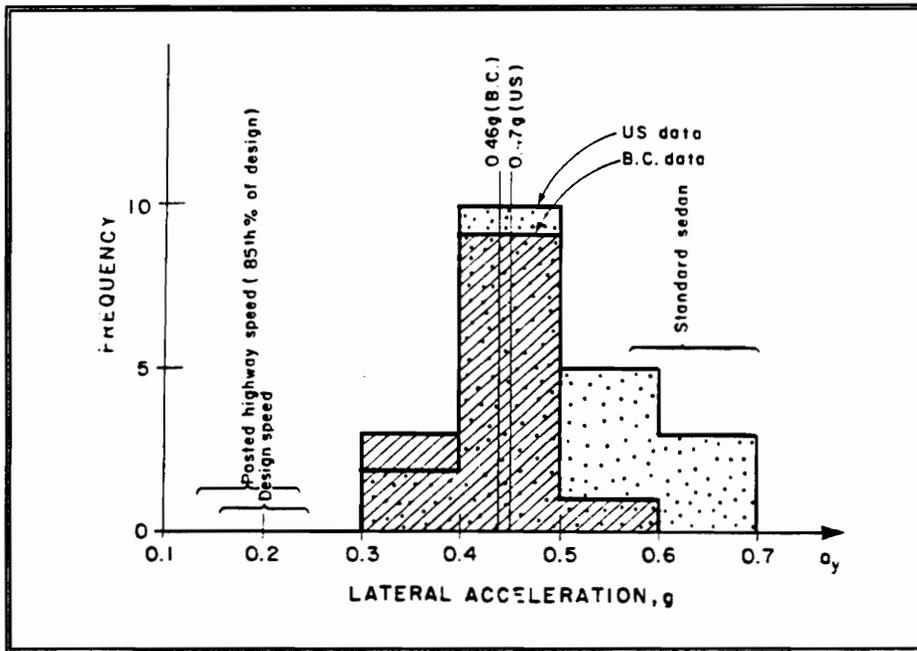


Figure 2.2.2.2: Lateral acceleration at rollover threshold experienced by trucks. [25]

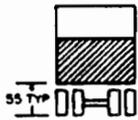
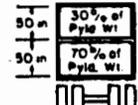
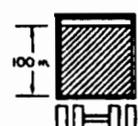
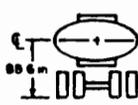
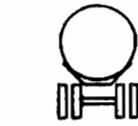
CASE	CONFIGURATION	WEIGHT (lbs)	PAYLOAD CG HEIGHT (in)	ROLLOVER THRESHOLD (G's)
		GVW		
A	 Full Gross, Medium-Density Freight (34 lb/ft ³)	80,000	83.5	.34
B	 "Typical" LTL Freight Load	73,000	95.0	.28
C	 Full Gross, Full Cube, Homogeneous Freight (18.7 lb/ft ³)	80,000	105.0	.24
D	 Full Gross Gasoline Tanker	80,000	88.6	.32
E	 Cryogenic Tanker (He ₂ and H ₂)	80,000	100.	.26

Figure 2.2.2.3 Rollover thresholds for different loading configurations [2]

The research concluded that the truck rollover thresholds values are actually less than the generally believed values of about 0.4g or more. These values for some of the trucks with particular loading configuration may be as low as 0.24g as shown in figure 2.2.2.3.

As implied in figure 2.2.2.3, the rollover threshold of a truck is largely a function of its loading configuration. The following parameters of a truck's configuration affect its rollover threshold:

- Center of gravity (CG) height
- Overall weight
- Longitudinal weight distribution
- Lateral weight distribution

Trucks with higher center of gravity have lower threshold values. Thus, low rollover thresholds may be a particular problem for trucks carrying low-density freight, which tends to fill the trailer before reaching the maximum gross vehicle weight. Trucks carrying high-density that does not fill entire trailer will generally will have lower centers of gravity and higher rollover thresholds. Illustration of rollover threshold values for two example vehicles used in the study by UMTRI [9] are shown in figure 2.2.2.4.

The final report of the study done by Ervin et al [9] observed the following:

1. The rollover threshold is decidedly reduced by increases in axle load limit.

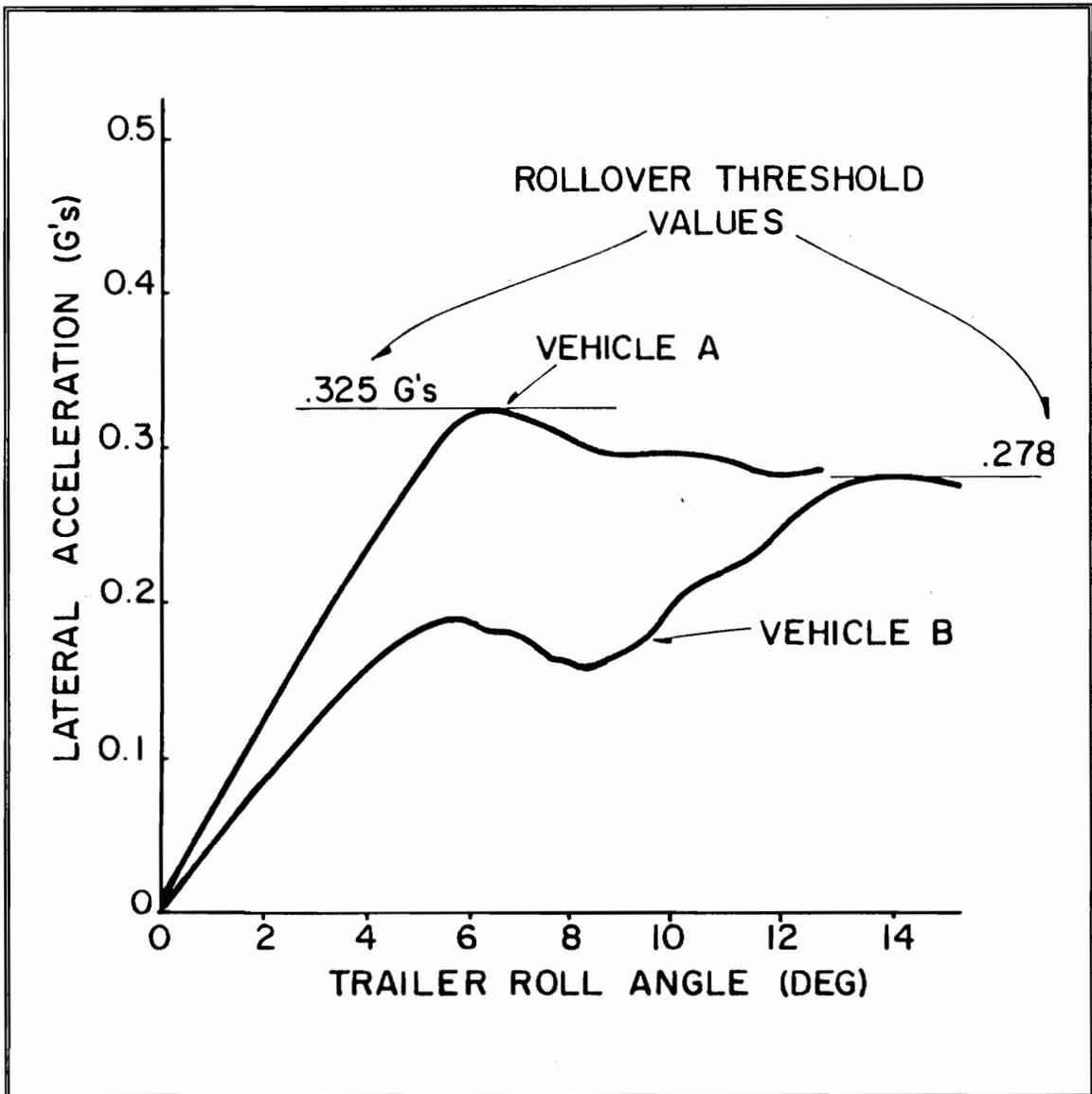


Figure 2.2.2.4: Illustration of rollover thresholds for two example vehicles [9]

- The decreases are approximately in proportion to the fractional change in the axle load limit which is represented. For the first three vehicles shown in figure 2.2.2.5, a 10% increase in axle load limit yields an average of 0.025 reduction in the rollover threshold.

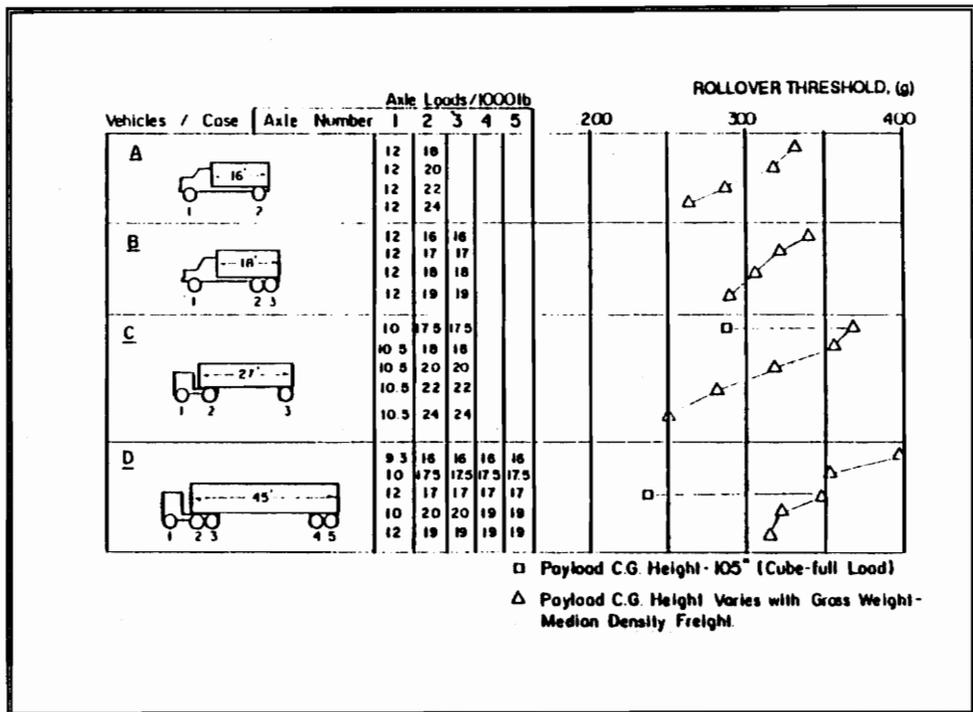


Figure 2.2.2.5: Influence of axle load variations on rollover threshold [8]

3. The steepest sensitivity of rollover threshold is seen in the case of the three-axle tractor-semitrailer. This result is partially explained by observing that with only a 27-foot trailer length, the rise in the payload c.g. height accompanying an increase in axle load on the tractor rear and tractor axles is the greatest of any of the vehicles shown.
4. Results of the five axle tractor-semitrailer show that rollover threshold show that rollover threshold reduces, at a given value of gross vehicle weight, as the tractor's load becomes distributed more towards the front. Thus, when a greater fraction of the load is borne by a suspension which is less able to contribute roll-resistance, the vehicle is permitted to roll through a larger angle as lateral acceleration increases such that a lower net rollover threshold results.

5. A more forward-biased loading on a truck or tractor tends to increase understeer level but decrease rollover threshold. The results for the five-axle tractor-semitrailer, however, that the influence of load distribution, per se, is not as strong as the influence of payload weight and c.g. height changes that accompany the increased loading.

The above results provide one set of measures describing the influence of axle load limits on rollover threshold. These measures reflect a particular baseline loading condition and also a specific scheme for relating the increased loading arrangement to a new placement of the payload. The study concluded that the actual influence of a load increase on the payload c.g. height could vary tremendously such that the range of possible influences of axle load limits on rollover threshold is great indeed. Figure 2.2.2.6. shows the plot of accident data which provides a clear view of the importance of the rollover threshold performance of heavy vehicles. This curve was derived from the accident data reported to the Bureau of Motor Carrier Safety of the USDOT over the years 1976 through 1979. The figure shows that a remarkable correlation exists between the percent of rollovers occurring among the single (SVA) involving tractor-semitrailers and the rollover threshold of each vehicle. Among the 9,000 accidents, more than 2,000 rollovers were recorded.

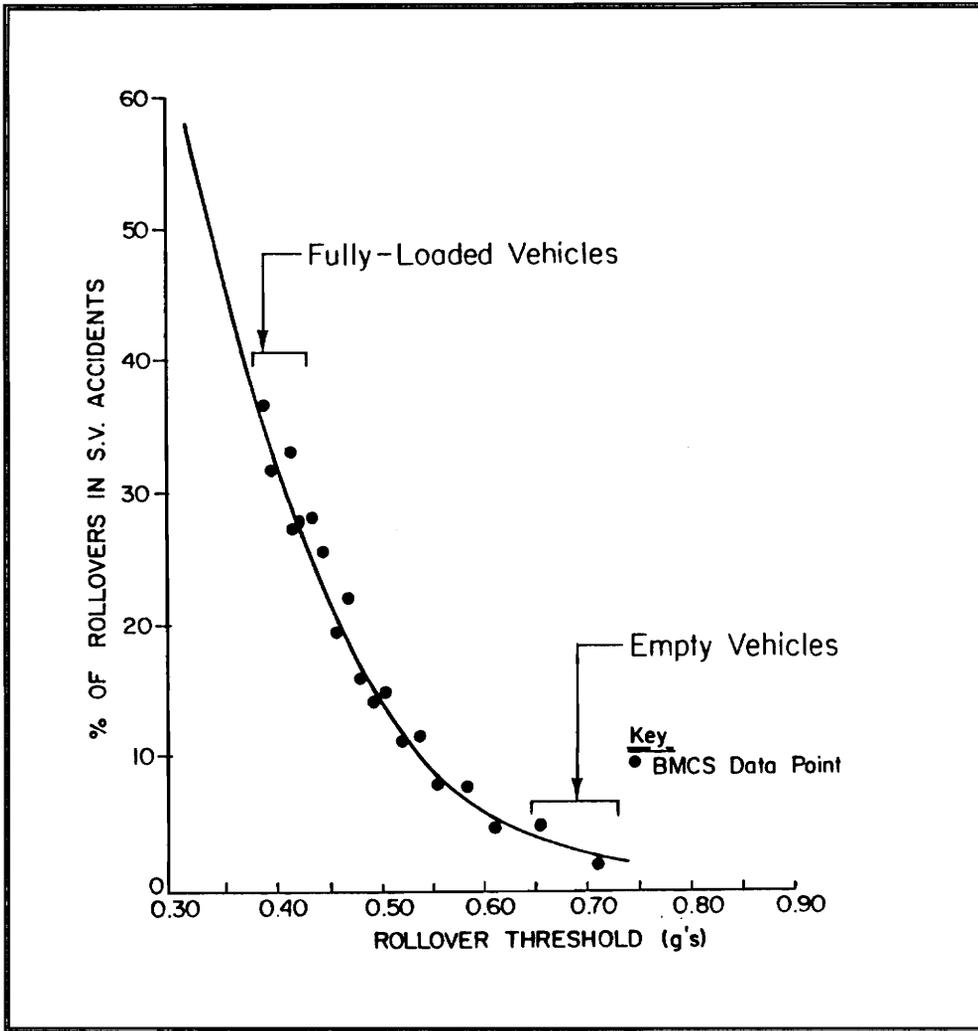


Figure 2.2.2.6: Percent of single -vehicle accidents in which rollover occurs as a function of the vehicle's inherent rollover threshold, in g's

2.3 Surface Conditions and the Changes in the Values of Friction Factor

Though the highway geometry is the major factor affecting the safety of heavy trucks, weather in the form of snow, ice, rain, sleet and fog has been a considerable factor, especially on the rural highways. Sudden changes in the

side friction values affect the stability of the trucks and cause rollovers are other accidents due to loss of control. Research was done in the past to estimate the friction factor values for different types of road surface conditions and tires. Tolerable levels of side friction factors have been determined primarily through the experiments addressing the threshold of discomfort for passenger cars. These studies have illustrated that the driver tolerance of net acceleration level experienced along the lateral axis of the vehicle, equal in g's to the side friction factor, declines with vehicle speed. In order to assure comfortable driving through curves, AASHTO [1] has defined maximum design values of side friction level as a function of speed. Based upon comfort considerations, these limits have been seen as affording ample levels of safety margin against the potential for "side skidding" in which the lateral forces developed by car tires might reach a friction saturation condition.

The current edition of the AASHTO policy on geometric design, side friction factor is permitted to go as high as 0.17 at a speed of 20 mph. Since the sum of superelevation value, e , plus the side friction factor, f , can be as high as 0.27, it is clear that the potential exists instantaneous value of (f) to reach 0.20 and above when the superelevation is being run off within the constant-radius curve. Figure 2.3.1 illustrates friction coefficients found by different investigators. Curves 1 to 6 form a study by Shelburne et al [1] in which more than 1,000 measurements of forward skidding were made on 32 pavements in both wet and dry conditions. Several types of tires were being used. Coefficients of friction were computed by using actual stopping distances in the standard stopping formula. Curves 7 and 8 are representative of several curves of a study by Moyer et al [23] in which over 50 surfaces were tested in the dry condition by three different methods using three types of tires. Curves 9 and 10 from the

same study are representative of wet pavements. Curve 11 is the calculated equivalent f value for stopping distance measured on high-type pavement these were the only tests that included stops from speeds of 60 to 70 mph.

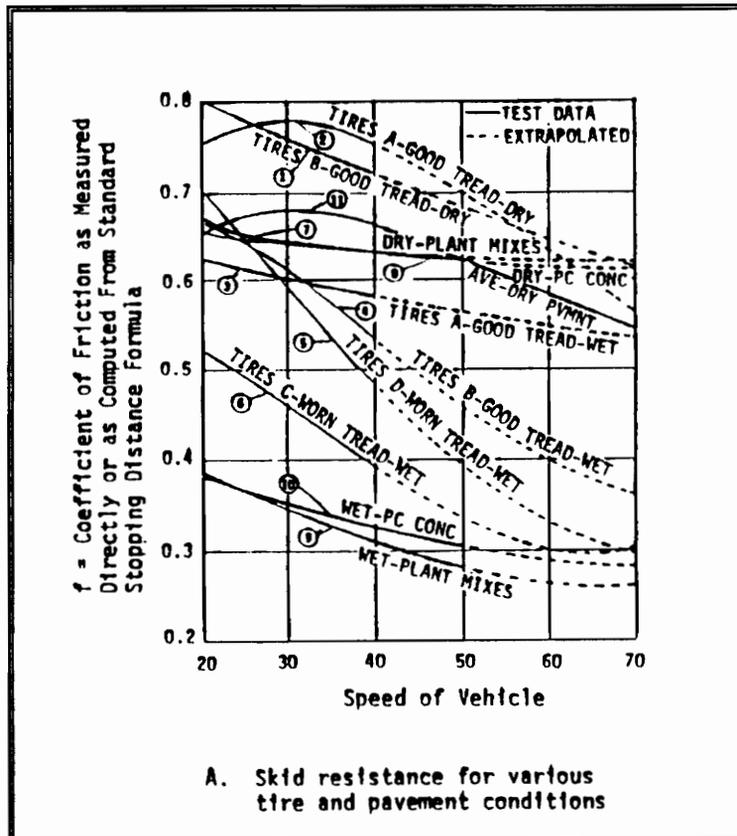


Figure 2.3.1: Skid resistance for various tire and pavement conditions [1]

Because of the lower coefficients of the friction on wet pavements as compared with dry, the wet condition governs in determining stopping sight distances for use in design.

With the wide variation in vehicle speeds on curves, there usually is an unbalanced force whether the curve is superelevated or not. This force results

in tire side thrust which is counter balanced by friction between tires and surface. The coefficient of side friction f is friction force divided by the weight perpendicular to the pavement and is expressed as the following simplified curve formula.

$$f = V^2/15R - e \quad \dots 2.3.1$$

The upper limit of this factor is that at which the tire is skidding or at the point of impending skid. Because highway curves are designed to avoid skidding conditions with a margin of safety, the f values should be substantially less than the coefficient of impending skid.

The side friction factor at which the side skidding is imminent depends on a number of factors, among which the most important are the speed of the vehicle, the type and the condition of roadway surface, and the type and condition of tires. In all cases the studies show a decrease in friction values for an increase in speed [1]. In a series of tests [23] it was concluded that safe speeds on curves indicated by side friction values of 0.21 for 20 mph, 0.18 for 25 to 30 mph and 0.15 for speeds from 35 to 50 mph. For higher speeds this factor was to be reduced on an incremental basis. Speed studies on the Pennsylvania turnpike [1] led to a conclusion that the side friction factor should not exceed 0.1 for speeds of 70 mph and higher.

Figure 2.3.2 summarizes the finding of the cited tests relating to side friction factors recommended for curve design. Although some variation is noted, all are in agreement that side friction factor should be lower for high speed design than for low speed design.

Where snow and ice are factors, tests and experience show that a superelevation rate of about 0.08 is a logical maximum to minimize slipping across the highway when stopped or attempting to slowly gain momentum from a stopped position. One series of tests [18] yielded coefficient of friction values for ice ranging from 0.05 to 0.200 depending on the condition of the ice, i.e., wet, dry, clean, smooth or rough. Other tests [23] corroborated these values. The lower value probably under thin film conditions (quick freeze) at a temperature of about 30°F in the presence of water on pavement. Similar low values may prevail with thin layers of mud on the pavement surface to permit hydroplaning. Tests on loose or packed snow show coefficient of friction ranging from 0.2 to 0.40.

Figure 2.3.3 shows the recommended values of the side friction factor for all rural highways and high-speed urban roads. These recommended values a reasonable margin of safety at high speeds and give some what lower rates at the low speeds than do some of the other curves.

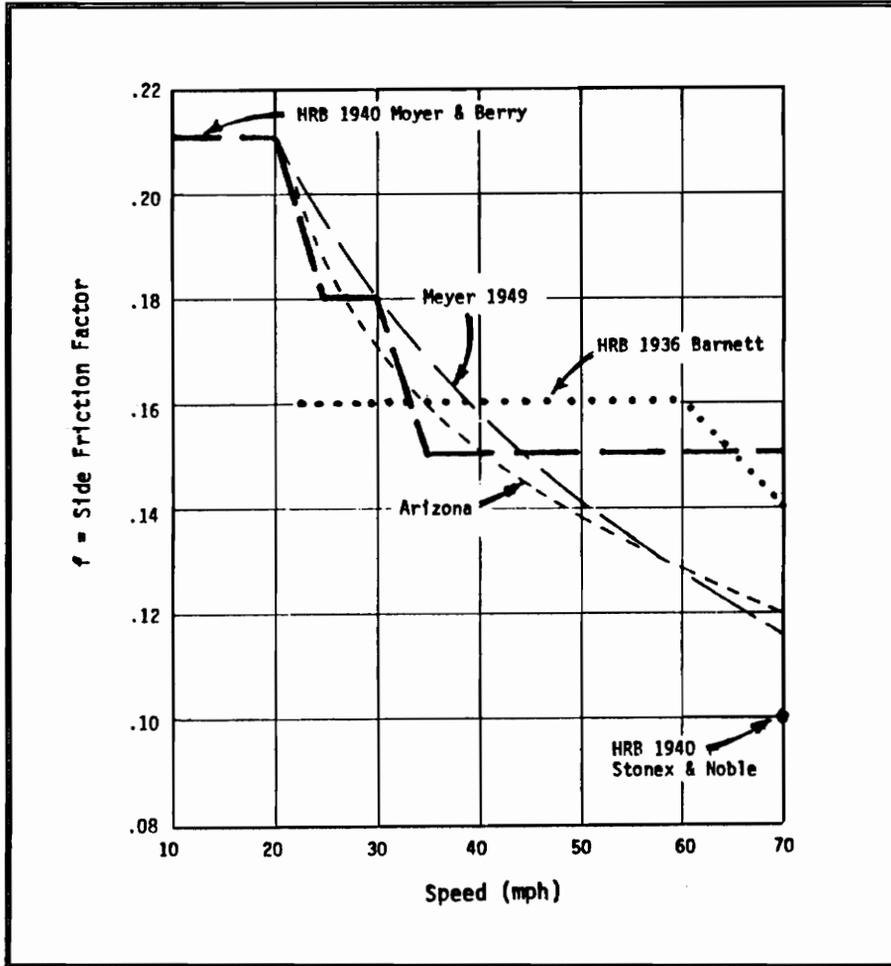


Figure 2.3.2: Side friction factors from different tests [1]

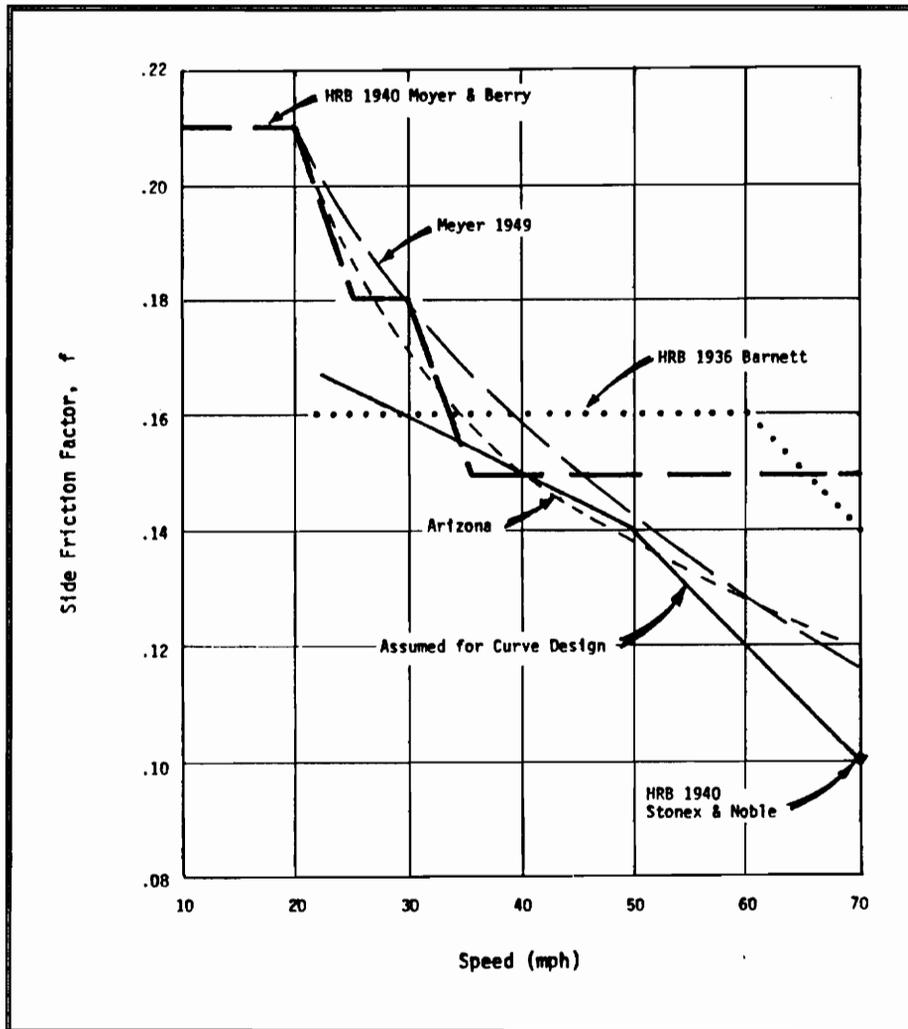


Figure 2.3.3: Side friction factors for rural highways and high speed urban streets [1]

2.4 Accident Models Developed in the Past

Very few accident models were developed in the relating the highway geometry to the truck accidents. Some of the notable are the ones by Fisher [15], Browner[3], Zeeger et al [30] and Garber [16]. All of these were statistical models relating truck ADT and road features like lane width, average paved shoulder width etc. to the no. of accidents. Most of these models considered highway geometry in general, only a few models like Browner's model particularly considered interchange geometry as affecting the truck safety on ramps.

In recent years simulation models were developed to test different kinds of trucks on highway sections with different geometric features and to decide the specific factors affecting the safety of the trucks. Simulation models are useful for testing the model before actual application. In the models developed by Ervin et al [2,8] at the University of Michigan Transportation Research Institute (UMTRI) ramp geometric features were represented in a complex simulation of the dynamic behavior of representative tractor semitrailer combinations. The calculated responses of heavy vehicles on each ramp tested were studied to illustrate how highway design may have influenced the known accident experience at the site. Model features included side friction factors, superelevation transitions, compound curves, deceleration lanes, ramp down grades etc. Potential counter measures for the identified problems were suggested.

2.5 Conclusions from the Past Research

Several researchers in the past developed regression models to relate the various geometric features and traffic variables affecting the safety of the trucks to no. of accidents. Several of these studies indicate that the effect of traffic volume overshadows that of a ramp geometric features. It should be noted, however, that these studies tended to focus on the effect of a single geometric feature on overall accidents, one at a time.

No through investigations were made of the effect of the factors influencing truck accidents alone, nor the effect on truck accidents due to interactions among these factors. In addition no studies were seen to have adopted in-depth methodology that would sufficiently explain the nature of the accidents. It appears that no prior investigators, except Ervin et al [2], have sought to examine the significance of ramp geometry by simulating the actual motion response of vehicles for the specific site layouts of accident involved road sections. Though the study done by Ervin et al was effective in addressing the accident experience, the effect of environmental factors was not at all considered in the simulation model. This study differs from prior work in the fact that it considers influence of not only the ramp geometry but also the effect of weather and surface conditions through direct simulation of vehicle response on example geometries.

3.0 METHODOLOGY

A graphics based computer simulation program is developed in order to simulate the trucks exiting from Interstate Ramps. Simulation is an effective way of pretesting systems, plans, or policies before developing expensive prototypes and actual implementation. Using computer based simulation, it is possible to trace out in detail the consequences and implications of a proposed course of action. In the past 20 years, simulation has proved again and again that it can be a powerful analytical tool. In small scale applications, it has recorded countless modest successes; in large scale applications, some of its successes have been spectacular and widely publicized. Discrete-event simulation is chosen over continuous simulation as it describes a system in terms of logical relationships that cause changes of the state at discrete points rather than continuously over time. Simulation can be defined as follows:

A simulation of a system is the operation of a model that is a representation of a system. The model is amenable to manipulation that would be impossible, too expensive, or impractical to perform on the system it portrays. The operation of the model can be studied and from it, properties concerning the behavior of the actual system can be inferred.

The main objective of this research is to test the trucks for different truck, geometric and surface conditions. The model which represents this phenomena is a complex one because of the changes in the system from time to time.

Simulation is an effective tool for modeling problems which may not be solved analytically or problems in which there is no fixed relationship among the components from time to time. The response of the trucks, moving on a ramp, to different surface and geometric conditions can be best represented by a simulation model rather than traditional models like analytical and numerical solutions. This study also involves simulating the ramp sections where actual rollovers were reported. A regression model or a numerical solution may be tedious or less effective for such an analysis. The flexibility of the simulation model can be utilized to effectively change the input parameters anytime during the simulation. For the above reasons, simulation approach is adopted in this research to predict the number of truck crashes.

A high level, powerful, free-form, English like simulation language SIMSCRIPTII.5 has been used in this research for the task of developing computer simulation model. SIMSCRIPT is used because of its versatility and user-friendly graphical interfaces. SIMSCRIPT was first developed by Harry Markowitz [26] and it has undergone various structural changes to make it more useful and easy to use especially, for the purpose of discrete event simulation. In particular SIMSCRIPT possesses the following features.

1. Articulate simulation goals.
2. Analyze the system to determine appropriate level of detail for the model.
3. Synthesize the system.
4. Collect and prepare input data.
5. Verify model correctness.
6. Validate the model results.

3.1 Model Structure

Simulation models exhibit many common properties. Every model has the following properties:

- A mechanism for representing arrivals of new objects.
- The representation of what happens to the objects within the modeled system.
- A mechanism for terminating the simulation

The arrivals of new objects into the system from the external world is usually independent of what happens within the system. This process can be characterized by describing the no. of objects that arrive simultaneously and specifying the time between arrivals. This is done by choosing either poisson or uniform distribution in the model and a frequency at which the trucks enter the system.

The primary focus of our modeling effort is the representation of what happens to the objectives within the modeled system. It is natural to focus on one object at a time and describe its interaction with other objects. For example, in our model trucks interacting with the geometry of the ramps or the highway.

Finally, a model must be provided with a means of termination. There are two methods of termination. The first is the planned-termination-time method, in which the termination is scheduled for a definite simulation time regardless of what else might be happening in the model. The second method is to allow everything in the model to come to rest. This research mode! follows the first

method of planned termination, and the simulation time has to be entered before executing the model.

3.2 Description of SIMSCRIPTII.5

SIMSCRIPT is a high level, English like, event oriented simulation language. The current version, SIMSCRIPTII.5, is revised by Alasdair [26]. The state of the system here is defined by entities, their associated attributes, and by logical groupings of entities. The dynamic structure of the system is described by defining the charges that occur at event times.

In SIMSCRIPT process concept is the primary dynamic object. The process is described below.

3.2.1 The Process

A process represents an object and the sequence of actions it experiences throughout its life in the model. There may be many instances or copies of a process in a simulation. There may also be many different processes in a model.

A process object enters a model at an explicit simulated time, its creation time. It becomes active either immediately or at a prescribed activation time.

In the model we have the following:

```
process GENERATOR
    activate a TRUCK now
```

`wait poisson.f(30,1) units`

Here the GENERATOR and the TRUCK are defined as processes. The WAIT statement defines the time between the creation time of two consecutive TRUCKS.

At each (re)activation of the process routine, it may execute statements representing the changes to the system state. The process routine may test for system conditions and take alternative courses of action. The process requests a quantity of any resource using a request statement as shown below.

`request 1 TELLER(1)`

If the requested quantity is available, it is given to the process immediately and the process continues the statement following the 'request' statement. Otherwise, the process will wait until the resources are available. After using the requested resource, the process may relinquish it as shown below.

`relinquish 1 TELLER (1)`

Processes interact either implicitly for example, through resource competition, or explicitly, through executing the statements to "activate", "interrupt" or "resume" one another.

3.2.2 The Resource

resources are the passive elements of a model. A resource is used to model an object which is required by the process objects. If the resource is not available when required, the process object is placed in a queue or waiting line and made to wait until the resource becomes available.

The simplest form of the resource consists of a single "unit" of a single type. For example, a one-teller bank or a single-runway airport might be modeled in this manner. Each resource also has the owner attributes for maintaining two sets.

Q.resource - is the set of processes currently waiting for this resource.

X.resource - is the set of processes currently using this resource.

U.resource - specifies the number of this resources currently available.

In this model the resource concept was not used as the model does not involve any queuing process.

3.2.3 The Program Structure

A SIMSCRIPTII.5 program consists of three primary elements.

1. A preamble giving a static description of each modeling element.
2. A main program where execution begins.
3. A process routine for each process declared in the preamble.

Each of elements are described below.

1. Preamble

The first section of any SIMSCRIPT model is the Preamble. It is purely declarative and it doesn't include any executable statements. All the modeling elements must be named in the Preamble. The following shows the declarations of modeling elements in the Preamble.

Preamble

```
process include GENERATOR and TRUCK
every TRUCK has a TYPE,
                a WEIGHT,
                a SPEED
```

The attributes of any truck can be accessed through references as TYPE(TRUCK), SPEED(TRUCK) etc. A particular truck is specified by the value of the variable TRUCK. Thus , EVERY statement defines a class of objects, each called TRUCK, having similar properties.

2. Main

Execution of a SIMSCRIPT program begins with the first statement in the Main program. Several necessary steps are taken in the Main program for a simulation. SIMSCRIPT requires that something be awaiting execution before a simulation commences. This is done by activating initial processes in the Main as shown below.

Main

```
call SET.DEFAULTS
activate a GENERATOR now
```

start simulation

A simulation begins when control passes to a system-supplied timing routine. This is done by executing the START SIMULATION statement. Any statements following this statement will not be executed until the simulation has terminated. At this point final reports could be produced and a new simulation could be run.

3. The Timing Routine

The timing routine is at the heart of discrete-event simulation. From a programming perspective, this is the routine that ties the entire collection of processes together. Let us define an "event" as a pending (re) activation of a process. Then the timing routine is as shown in figure 3.2.3.1

As can be seen from the figure, processes must be on the pending list prior to entry into this routine or the simulation will terminate immediately. It is natural to assume that the execution one process will activate other processes and thus perpetuate this sequence for some time. Termination will occur either for the algorithmic reason shown in the figure or because of a STOP statement.

4. Process Routines

Each process declared in the program preamble must be further described by a process routine. From a programming point of view, the process routine embodies the logic description of a process, telling what the process object does under all circumstances. Information pertinent to each process-instance is stored with the process notice giving, for example, the values of local variables in the routine and the time at which the process routine will next reactivate.

5. Entities and Sets

Entities are modeled as either permanent or temporary. Permanent entity is used when the number isn't likely to change during the simulation run. A temporary entity is used when the number is likely to change. Sets contain a group of temporary entities and it is owned by a permanent entity as shown below.

Define AIRLINE as a permanent entity

 Define AIRPLANE as a temporary entity

every AIRLINE has an AL.NAME

 and owns a FLEET

Define FLEET as FIFO set

every AIRPLANE has a AP.NUMBER

 and belongs to a FLEET

6. variables

SIMSCRIPT variables are of numerous types. Attributes, reference variables, and simple variables are only a few of the types available, but they will suffice to introduce the concepts. Variables are either global or local in scope. Global variables are defined in the Preamble. If a variable is not explicitly defined anywhere, it becomes a local variable in the routine it is defined. All variables have a mode. If the mode is not defined, the default mode is assumed to be Real variables.

in the following expression,

 normally mode is undefined

mode is not assigned in the beginning so as to define the mode any time later in the program. Mode can be assigned as shown below.

Define TYPE as a text variable

Define SPEED,

WEIGHT as real variables

A variable is assigned a null value by the program until it is explicitly assigned a value.

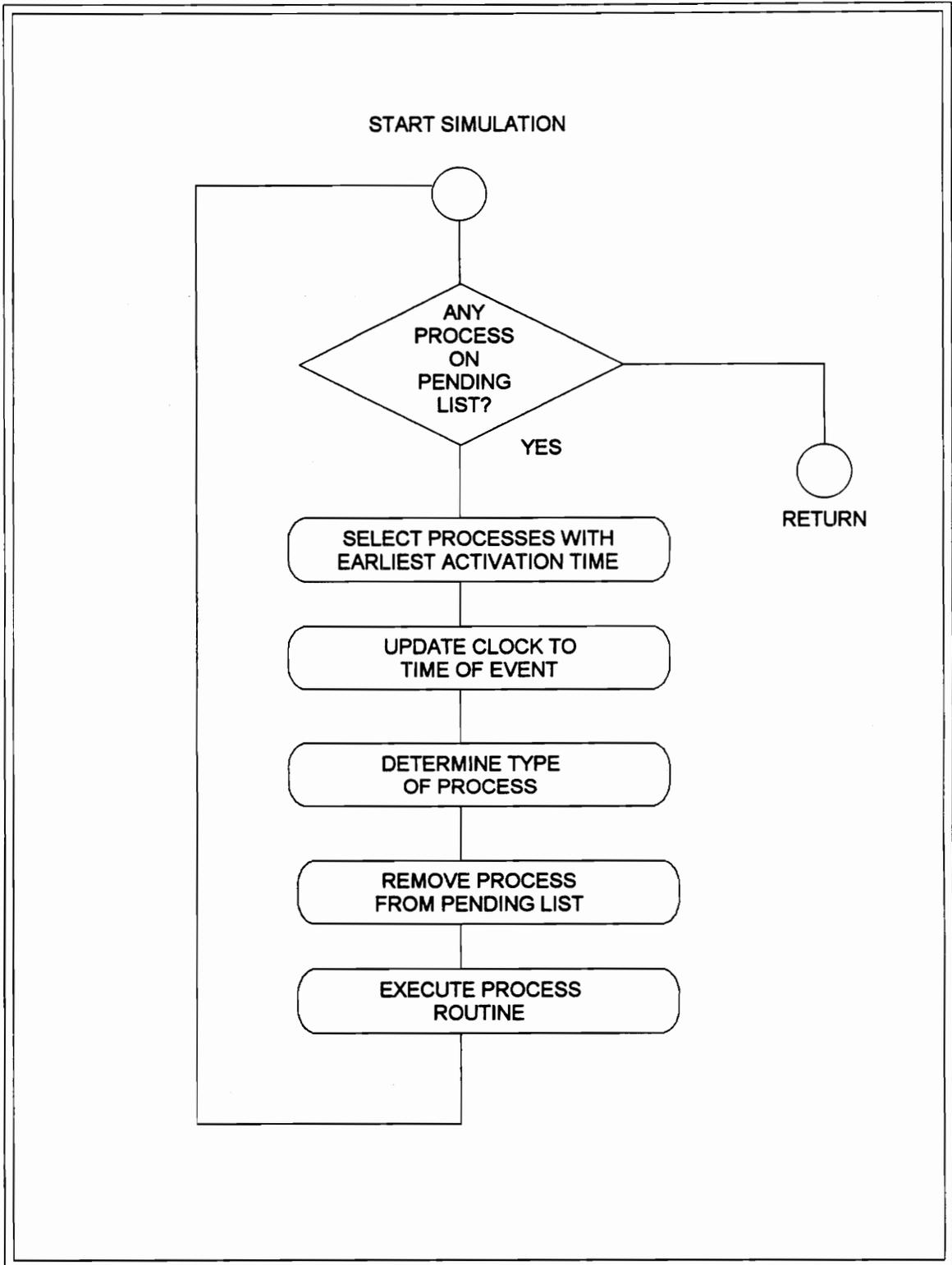


Figure 3.2.3.1: Basic SIMSCRIPTII.5 Timing Routine [26]

6. Random Phenomena

Random numbers are generated by using the library functions of SIMSCRIPT. The function RANDOM.F () generates random numbers from the interval (0,1). The random deviates can be represented by functions like UNIFORM.F(), NORMAL.F(), GAMMA.F(), BINOMIAL.F() etc., for respective probability distributions as shown below

```
let X = Poisson.f( $\mu$ , 1)
```

where μ is the mean of the distribution and '1' is the seed tag.

7. Other Library Functions

SIMSCRIPTII.5 has many in-built library functions and constant which makes the language simple to use. For example square root and the absolute value of a variable can be represented as follows. The constant PI.C represents the value of π .

```
let X = ABS.F(Z - PI.C)
```

```
let Y = SQRT.F(X**2 - Z**2)
```

Though the SIMSCRIPTII.5 is popular for its discrete event simulation, it has continuous simulation capability as well. Given an equation for the rate of change of a variable, it calculates the value of the variable and continuously checks the conditions. This is the basis for continuous simulation. For example the following SIMSCRIPTII.5 code shows a typical continuous simulation model.

```
Process SHAPE
```

```
work continuously evaluating 'EQUATIONS' testing 'QUIT'.
```

3.2.4 Graphical Interface and Animation

The goal of system simulation is to increase the understanding of the operation of a complex system. Unfortunately, the results of simulation studies are often presented ambiguously. The complexity of the system and the simulation can make it difficult for users and decision makers to fully appreciate the interactions between system elements. Results are often not well understood. Premature action may be taken based on invalid assumptions, incorrect data, or hidden modeling errors. Conversely, valid simulation results may not be quickly appreciated.

Often the best way to represent a dynamic system is with use of graphics. Animated graphics clearly show the operation of the simulated system and the graphic results are easily evaluated. System operation is better understood, and decision makers have more confidence in the simulation results.

Graphical representation facilitates debugging. Coding, data or modeling errors usually are apparent, thus avoiding the need for tedious error tracking.

These are some of the reasons for choosing the graphics based animation for the simulation model. The SIMGRAPHICS are described below.

SIMSCRIPTII.5 has the capability of static or dynamic presentation of graphics, interactive graphics and animated displays. This is done with the help of SIMGRAPHICS, an extension of SIMSCRIPTII.5. The typical applications include [CACI, 1991]:

1. Data Presentation

Histograms, pie charts, X -Y plots, and other graphics can be generated to display numerical or statistical information.

2. Model Representation

Animated graphics can represent the system under simulation and evolve as the simulation progresses.

3. Run Configuration

Simulation experiments start from some initial conditions, which can be easily set by manipulating a graphical representation of the system. Interactive reconfiguration at run-time can reduce the iterations needed to achieve stable results, and make simulation progress more general. Asynchronous input allows the user to alter the scenario as it runs.

4. Presentation Graphics

Smart icons such as clocks, dials, and meters allow us to view changes in speed, altitude, or queue size as the simulation runs. Histograms, pie charts line graphs, and trace plots concisely display the results of the simulation.

5. Graphics for Animation

Creating detailed graphic shapes is as easy as drawing the shape on the screen with a mouse. Once created, these shapes can be tied to SIMSCRIPT entities. An entity's icon is automatically animated and updated to represent its current state. Animated entities are defined as following in the Preamble:

Define TRUCK as a dynamic graphic entity

and the following lines of the source code,

Create a ROAD

show ROAD with "COLROD.ICN" at (500, 1000)

create the temporary entity called the ROAD and show it with the given graphics file.

The statement

Erase ROAD

erases the particular ROAD from the graphics screen after its usage.

6. Forms

Forms can be created with the graphics editor to manage user interaction. This feature allows the user to easily create elegant user interfaces. The following source code activates the parts of the Form.

Define FORM.PTR as a pointer variable

Define FIELD.PTR as a pointer variable

show FORM.PTR with "R1.FRM"

let FIELD.PTR = dfield.f("SIM.TIME", FORM).

4.0 MODEL DESCRIPTION

This chapter deals with the description of the simulation model developed as part of this research. The description includes assumptions and boundaries of the model, input and output parameters, mathematical computations involved and algorithms of the simulation and in the end, description of some of the important routines of the program.

The simulation model should be formulated in such a way that it is easy to understand and it should reflect important characteristics of the real system in the best possible way. The amount of detail included in the model was based on the purpose for which the model was built. Only those elements that could cause significant differences in the decision-making process are considered. Graphics based computer animation is used in developing the model to make it the program easy to understand.

4.1 Model Assumptions

To simplify the system, and yet capture the essence of the system being modeled the following assumptions were made:

1. The truck arrivals are generated randomly according to either poisson or uniform distribution. They are generated at a frequency given by the user. The frequency can be changed any time during the simulation.
2. The trucks are generated at a distance of about 1000 ft. a head of the ramp.
3. The speeds of the trucks are assumed to be uniformly distributed between a given range. The range can be changed while the simulation is underway.
4. 3 types of trucks are assumed in the model and their weights range from 34,000 lbs to 90,000 lbs.
5. About 50% of the total trucks take the exit ramp. This assumption is made as our major concern is about the trucks taking the ramps.
6. Acceleration and deceleration values of the trucks are assumed according to the AASHTO recommendations.
7. There is no wind affect.
8. Friction factor values are assumed according to the AASHTO recommendations for different weather conditions.
9. Passing is not allowed.
10. Vehicle population consists only of trucks.

4.2 Model Parameters

The output of the simulation model is a function of various input parameters.

The parameters of the model are described below:

1. Truck arrival rates:

The user can choose the frequency of the truck arrivals. The frequency can also be changed during the simulation. As most of the traffic arrival pattern resembles either uniform or poisson distribution, trucks are generated according to one of the above (chosen) distributions.

2. Truck Speeds:

Speeds are chosen randomly from a given range. This range is given as 55 - 65 mph. Although the speed limit for trucks on the interstate highways is 55 mph, according to the studies done in the past, more than 90% of the trucks exceed the speed limit of 55 mph. This limit can be changed during the simulation to test the trucks for different speeds.

3. Surface condition:

Surface conditions of the pavement can be input and changed during the simulation. Friction factors are randomly allocated to the model according the surface conditions, dry, wet, and icy. Friction factors are chosen according to AASHTO recommendations. These values are shown in Table 4.2.1

4. Radii of the ramp curves:

Radii of the ramp curves can be changed anytime during the simulation. The program alters superelevation development according to the radius of the curve. The radius is a key factor in deciding the lateral acceleration of the trucks moving on the ramps.

5. Types of trucks:

The program generates 3 kind of trucks, single unit, semi-trailer and tractor trailer, according to given proportions. Each truck is allotted a weight depending up on its type. The weight of a single unit truck ranges from 34,000 to 50,000 lbs, and that of semi-trailers ranges from 70,000 to 85,000 lbs and the tractor trailers' weight ranges from 75,000 to 90,000 lbs.

6. Height of center of gravity of the truck load:

The pay load height is assigned to each truck randomly depending on the weight of the truck and type of the truck. The model assumes the values from a study done by Barnes et al [2] for different loading configurations and the weight of the trucks. For example, a single unit truck with a typical loading configuration (40,000 - 50,000 lbs) has its payload at 70 to 90 in. and a Semitrailer weighing about 80,000 lbs with uniform axle loading has its payload 70 to 95 in. from the ground. These values cannot be changed while the simulation is running. In order to change these values input files are edited.

7. Other truck and road parameters:

Other truck and road parameters involve acceleration and deceleration rates of the trucks, truck dimensions, superelevation development, length of the highway, width of the lanes, vertical alignment and grades are input through the input files and they cannot be altered during the simulation. Input files can be altered before running the program but the program needs to be recompiled.

Design Speed	Maximum e	Maximum f	Total (e+f)	Maximum Degree of Curve	Maximum Radius
20	0.06	0.17	0.23	49.25	116
30	0.06	0.16	0.22	21	273
40	0.06	0.15	0.21	11.25	509
50	0.06	0.14	0.20	6.75	849
55	0.06	0.13	0.19	5.5	1,061
60	0.06	0.12	0.18	4.25	1,348
65	0.06	0.11	0.17	3.5	1,637
70	0.06	0.10	0.16	2.75	2,083
20	0.08	0.25	0.25	53.5	107
30	0.08	0.24	0.24	22.75	252
40	0.08	0.23	0.23	12.25	468
50	0.08	0.22	0.22	7.5	764
55	0.08	0.21	0.21	6.0	960
60	0.08	0.20	0.20	4.75	1,206
65	0.08	0.19	0.19	3.75	1,528
70	0.08	0.18	0.18	3	1,910

Table 4.2.1: Design standards of AASHTO for horizontal curves and ramps

4.3 Description of the Ramps:

1. Ramp I

This ramp is a compound curved ramp consisting of three different curves with a total turning angle of 90 degrees. This kind of ramps are often designed because of the space constraints. In the program, the ramp is designed according to AASHTO design standards of 1990 green book. It consists of three curves with respective radii of 420, 210 and 105 ft. These radii are input as the default values in the program, the radii can be changed any time during the simulation. Lengths of the taper and deceleration lane are 275 ft and 375 ft respectively. The rate of deceleration on the taper is assumed to be about 1.5 mph/sec. On the deceleration lane and ramp curves it varies from 2.5 - 3.5 mph/sec. As the curve with minimum radius is designed for a speed of 25 mph, the safe speed is about the same on this ramp. Superelevation is developed about the center line of the curve with a maximum rate of 0.08 ft/ft.

Although the ramp seems to be designed well, it poses a threat to the trucks due to abrupt changes in the curvature, and insufficient deceleration length. The ramp was designed mainly considering the passenger cars which have better acceleration and deceleration capabilities. It may not be possible for trucks traveling at speeds higher than 60 mph to reduce the speeds to 20-25 mph using the provided lengths of deceleration lanes. During the wet weather conditions, safe speed limit will be still lesser, making it almost impossible for trucks traveling at higher speeds to reduce their speeds in order to avoid rollovers.

2. Ramp II

This is an existing ramp on I-81 located at Rockingham county in Southwest Virginia. Two accidents involving truck rollovers were reported between 1986-89 on this ramp. The ramp consists of two circular curves, with respective radii of 230 ft and 911 ft. The taper and deceleration lengths combine to make a total effective deceleration length of about 600 ft. The first curve length is about 600 ft and that of the second curve is about 1100 ft. The superelevation rate is 0.08 ft/ft developed about the center line of the roadway. The posted speed limit is 30 mph. The speed limit on the highway for that section is 55 mph. The vertical grade of the ramp is about 2%.

insufficient deceleration lane length and sudden changes in the curvature without any transition are the major concerns for the safety of the trucks taking this ramp. One of the accidents reported was during the wet weather conditions. The accident was caused due to rollover of the truck even though the truck was traveling at a speed of 30 mph. The posted speed limit could be blamed for the accident as it was done considering only the passenger vehicles. Though the posted speed limit is good enough for trucks to pass by safely during the dry surface conditions, the wet weather poses considerable threat to the trucks traveling at speed equal to or higher than the posted speed. Another major concern is the development of superelevation and the vertical grade. Though the vertical grade is small, it affects the stability of the trucks considerably during the wet surface conditions.

As this ramp differs in geometry and in the nature from the first ramp, this has been considered as a good test site to evaluate the model.

3. Ramp III

The third ramp in the program is an offset of the cloverleaf at the intersection of I - 95 and route 17 near Stafford county in Virginia. This ramp differs from first two ramps because of its reverse curvature. The ramp consists of two circular curves of equal radius of about 600 ft. The deceleration lane and the taper length together make up an effective deceleration length of about 625 ft. Both the truck rollovers reported in recent years on this ramp were during the dry surface conditions. The total length of the ramp is 1400 ft and the superelevation rate is 0.08 ft/ft. The vertical grade and the posted speed limit are - 3.3% and 35 mph. respectively. The average traffic volume for the intersection is about 9730 vph. The degree of curvature for each curve is 18.23° .

Sudden changes in the curvature can be blamed for both the rollovers reported on this ramp. One crash was reported at the beginning of the first curve and the other at the beginning of the second curve. Because of the large radius of the first curve, drivers may travel at a higher speed than the posted speed limit, without knowing about the reverse curve a head and ending up in a loss of control situation. One of the accidents was reported at a speed of 50 mph, 15 mph more than the posted speed limit. Other reasons could be the length of the deceleration lane, superelevation development, and the vertical grade combined with the horizontal curvature. Additional changes for the curvature were proposed and they are being implemented to improve the safety of the trucks exiting from this ramp. As the nature of this ramp is different from the above two ramps, this has been selected to test and evaluate the simulation model. The following figure shows the layout of this ramp.

4.4 Computations

The simulation involves several computational routines. The major routine is the one which deals with the dynamics of heavy duty trucks traveling on a ramp. The assumptions and the rollover mechanics of the heavy vehicles are explained below.

4.4.1 Dynamics of Heavy Vehicle rollovers

The rollover of heavy vehicles can be looked upon as deriving from a variety of possible stimuli. To begin with the fundamentals, it is useful to consider a rigidly suspended vehicle in the beginning as shown in the figure. This applies to any rigid vehicle unit having a single roll degree of freedom. A tractor semi - trailer approximately meet this stipulation, assuming that tractor and the semi - trailer together as a single unit.

Figure 4.4.1.1 shows the dynamics of a rigidly suspended vehicle

The figure identifies the following:

W - Vehicle weight.

A_y - Steady lateral acceleration.

T - Half track width of the vehicle.

h - height of the center of gravity above the ground

ϕ - vehicle roll angle.

It is assumed that the vehicle achieves a steady lateral acceleration condition by means of lateral tire forces in the ground plane.

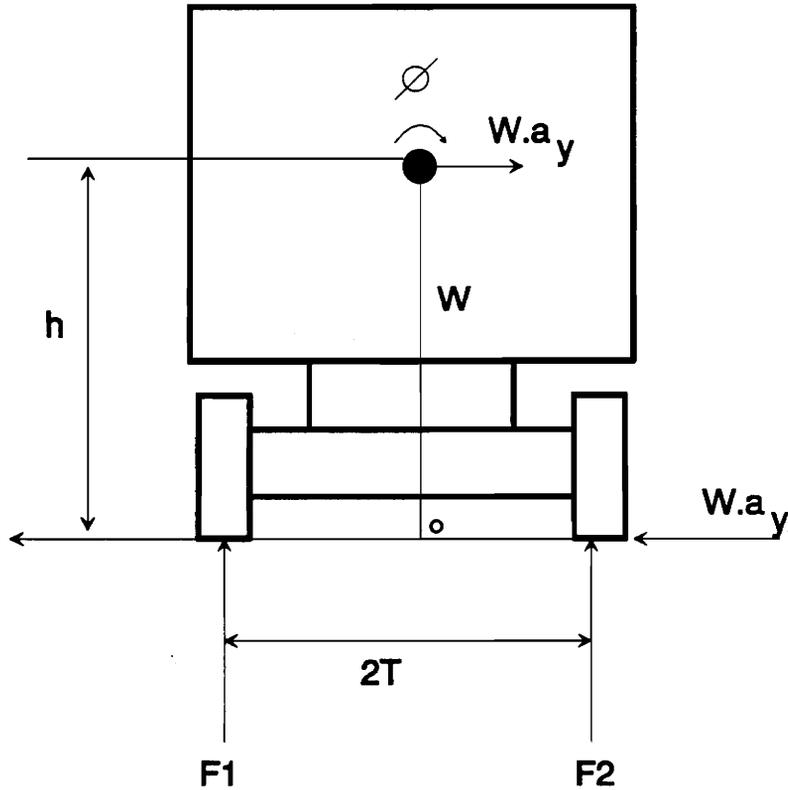


Figure 4.4.1.1: Dynamics of a rigidly suspended Truck

In this condition three moments act on the vehicle. If we consider the moments about point 'o' in the figure and if we assume small roll angle such that $\tan\phi \cong \phi$, these three moments are:

- W A_y h The primary overturning moment generated by means of a steering maneuver having a lateral acceleration level A_y .
- (F2 - F1) T The restoring moment, arising due to a lateral transfer of vertical load between the left and right side tires.
- W h ϕ the lateral displacement moment, deriving from the roll motion which displaces the center of gravity laterally towards the outside wheels.

The summation of these moments satisfying steady-state equilibrium yields the expression:

$$w A_y h = (F_2 - F_1)T - W h \phi \quad \dots(4.4.1.1)$$

The vehicle will become unstable when the moment due to lateral acceleration exceeds the net stabilizing moment. When the stabilizing moment is maximum, we observe that the term $(F_2 - F_1)T$ has the maximum value of WT . This is achieved when the total vertical load is transferred to the outside wheel. For the represented case of the rigid vehicle this complete load transfer occurs with zero roll angle. When the overturning moment exceeds the maximum restoring moment WT , the rigidly - suspended vehicle begins to exhibit a roll angle response.

One can characterize the static roll stability of a vehicle in terms of "roll over threshold", which is the maximum value of lateral acceleration the vehicle can tolerate before rolling over. In case of the rigidly suspended vehicle, the rollover threshold is defined by

$$A_y = t / h \quad \dots(4.4.1.2)$$

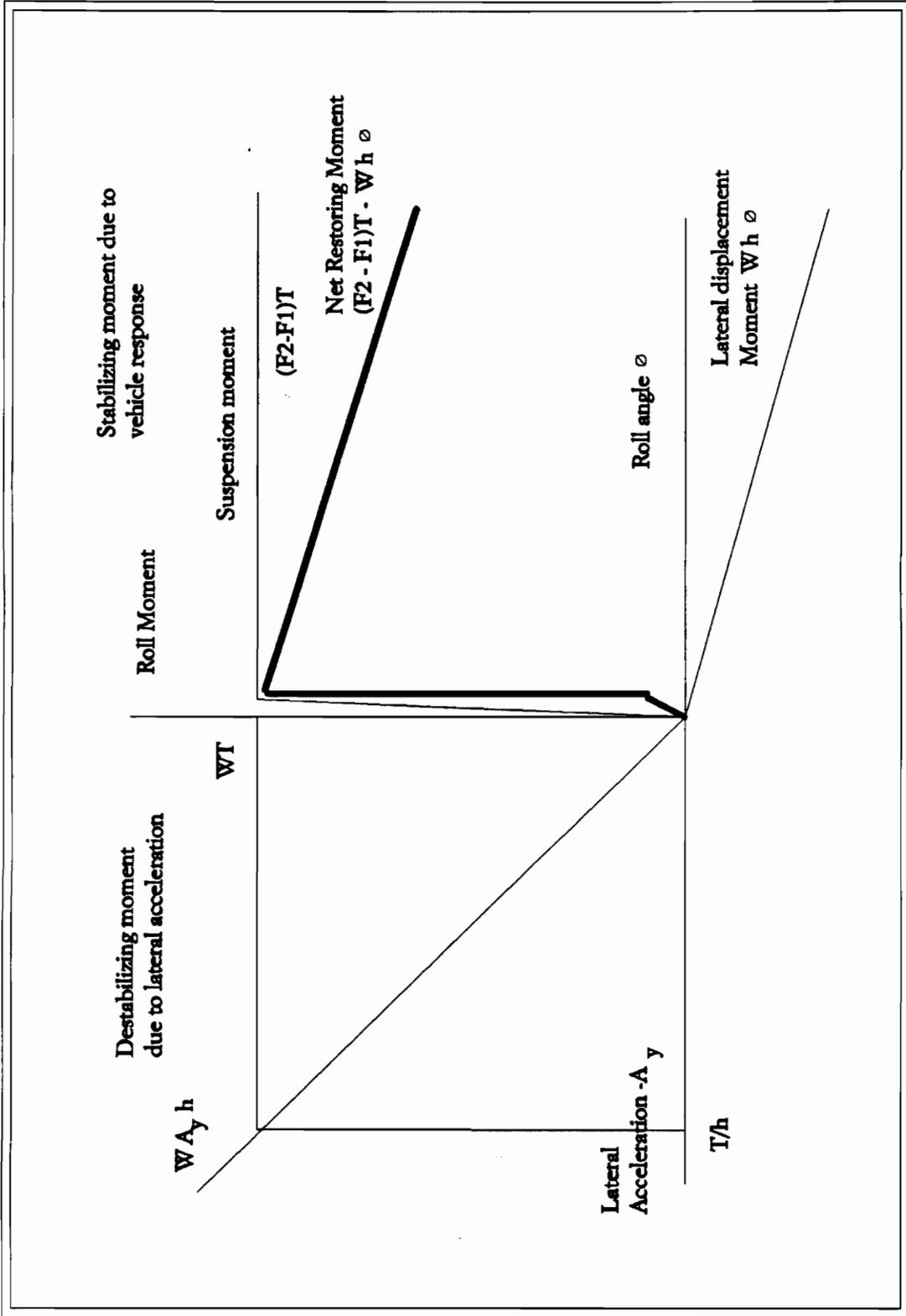


Figure 4.4.1.2 Graphical representation of rigidly suspended truck rollover dynamics [8]

This phenomena is graphically shown in the figure 4.4.1.2.

Now, consider the case of a vehicle which is suspended upon compliant tires and suspension springs. In this case it is convenient to assume that the rolling motion of the sprung mass on the tire and suspension springs takes place about a center which is in the ground plane, at the mid-track position. Another assumption here is that the total mass of the vehicle is in the sprung mass.

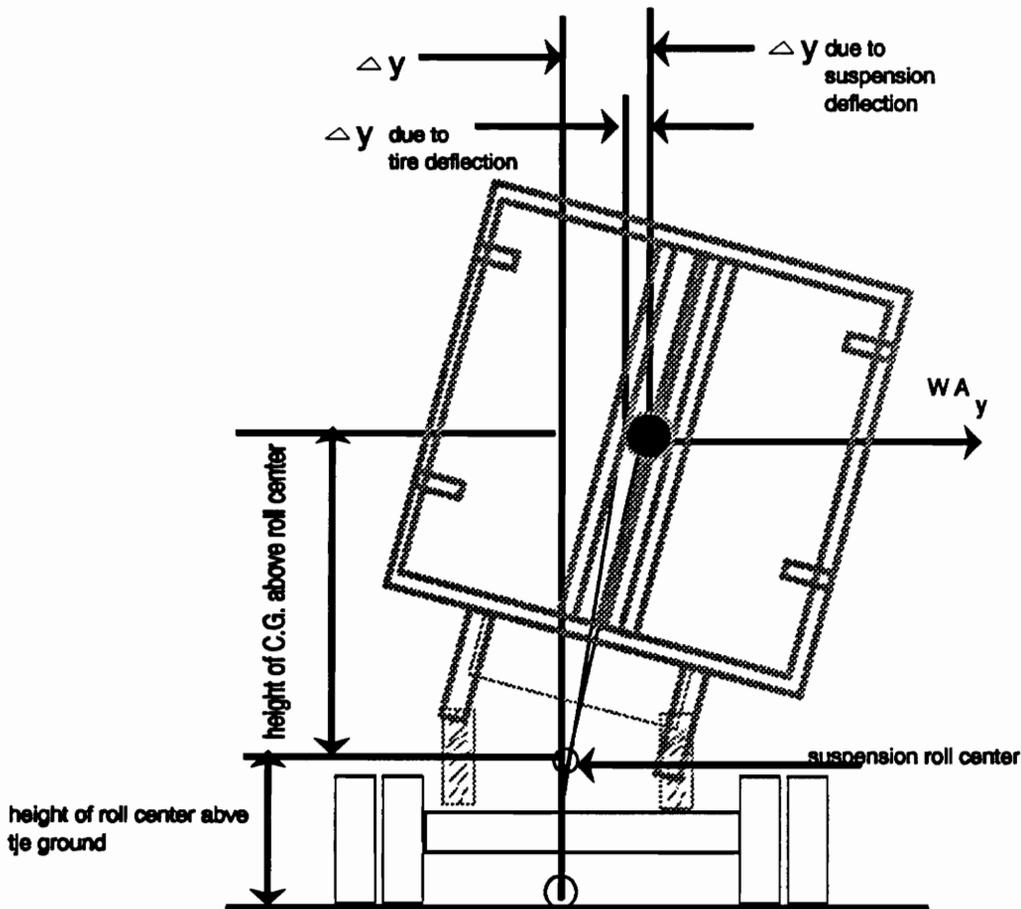


Figure 4.4.1.3: Dynamics of a truck suspended on compliant tires and springs.

Layout of this vehicle is shown in the figure 4.4.1.3 and this phenomena is shown graphically in figure 4.4.1.4. Here the maximum restoring moment, WT , cannot be attained until the roll angle is ϕ_l . At this roll angle, However, the lateral displacement moment, $-Wh\phi_l$, is developed such that the net restoring moment is decreased to the value $(WT - Wh\phi_l)$. Accordingly the rollover threshold value is reduced to:

$$A_y = (T - h \phi_l)/h \quad \dots(4.4.1.3)$$

Clearly the rollover threshold value becomes more reduced in the case of softer suspensions, which must be deflected through a larger value of the roll angle. The rollover threshold is further reduced due to spring suspensions, fifth wheel lash and frame compliances, cargo shifts. The influences which determine the actual rollover thresholds are shown in the figure 4.4.1.5.

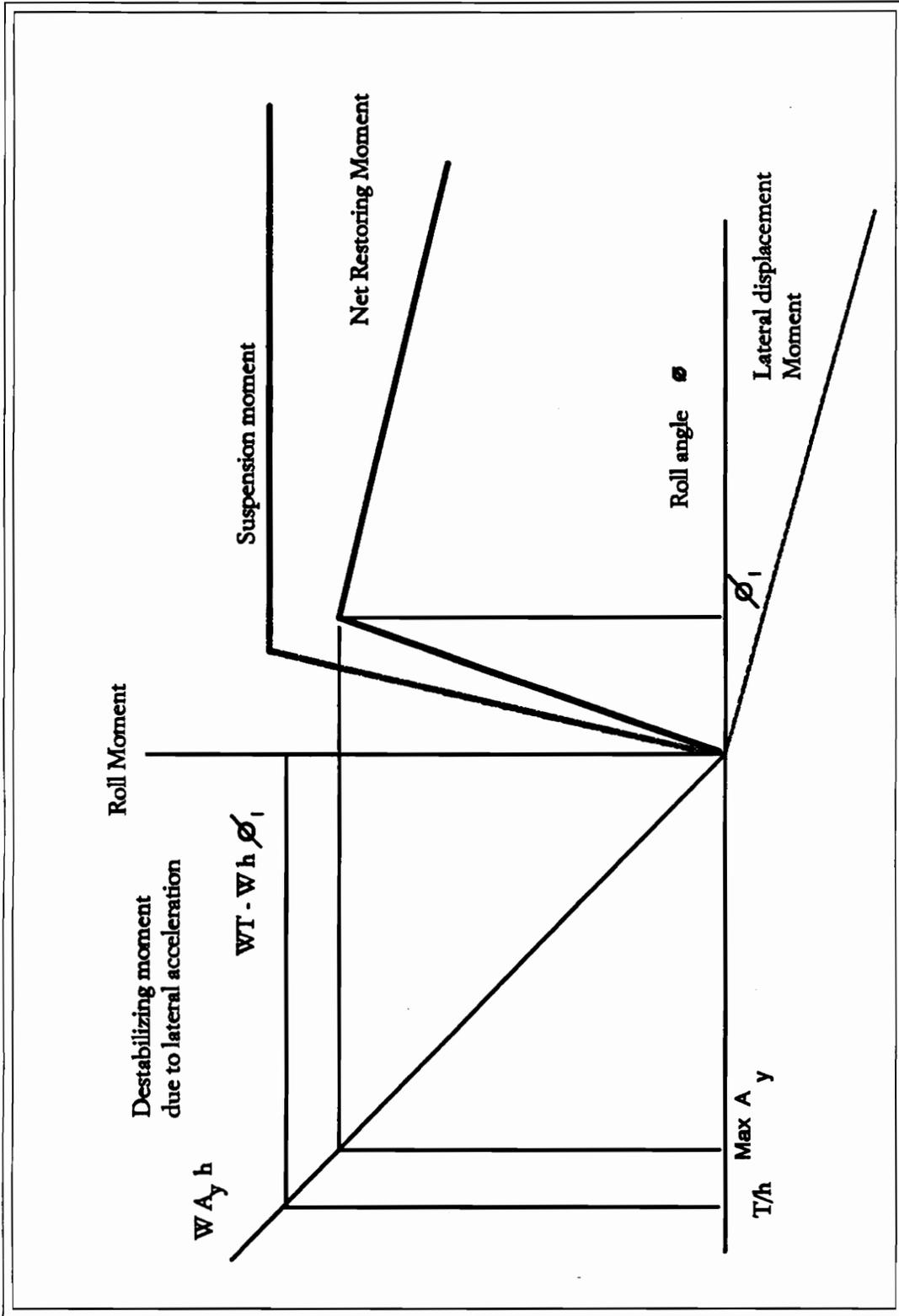


Figure 4.4.1.4 Graphical representation of truck rollover dynamics suspended on compliant tires and springs [8]

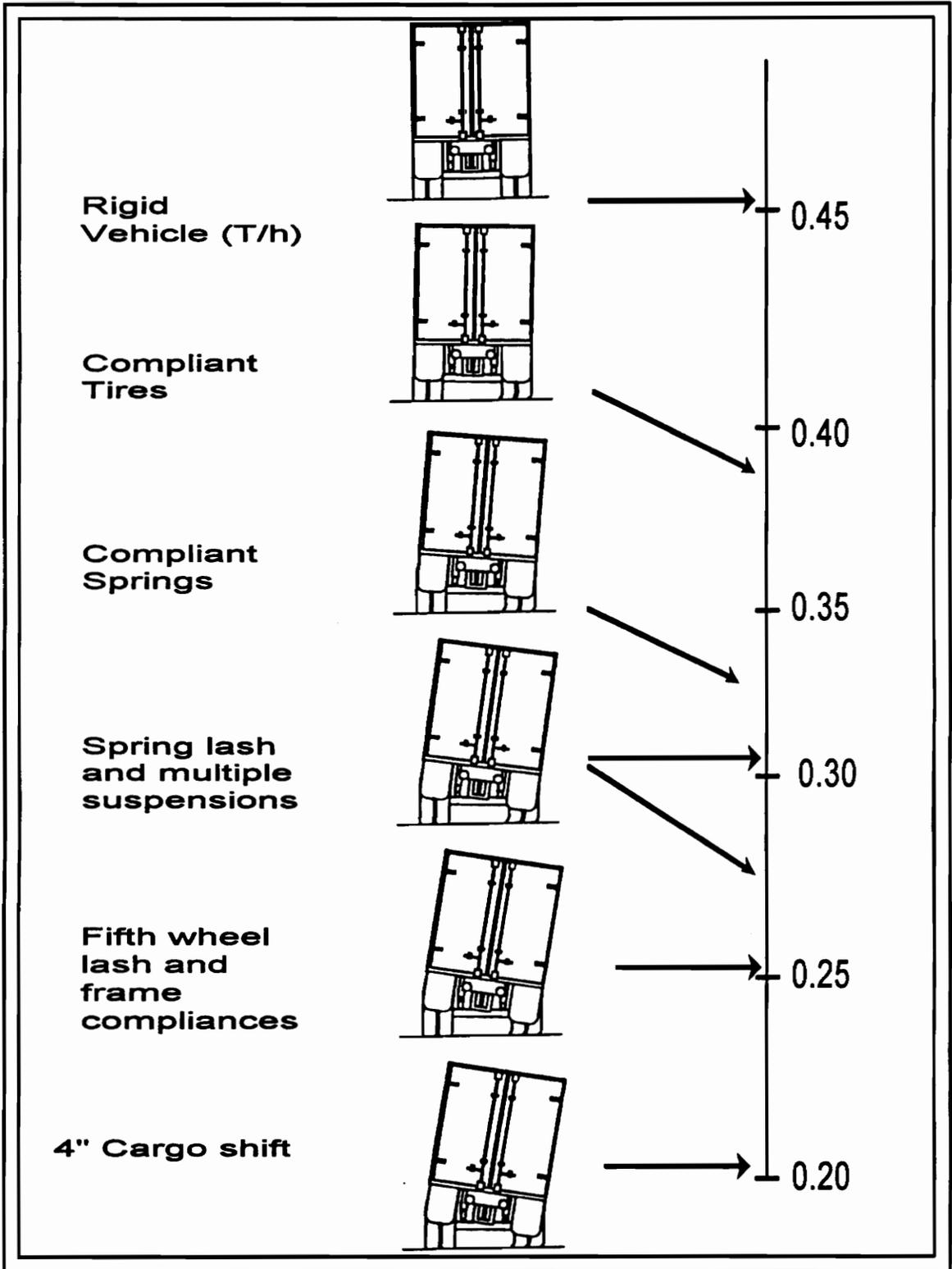


Figure 4.4.1.5: Influences of various factors on the rollover threshold values [8]

4.5 Program description

The trucks in the model are generated according to the user selected inter-arrival distribution. The program has an easy to use graphical interface which was developed using SIMGRAPHICS. Most of the input values can be altered during the simulation using the menubar. Before the program and its logic is described the modeling of some of the major routines is briefly described below.

4.5.1 Preamble

Preamble is the first part of the SIMSCRIPTII.5 program where all the global variables, entities, processes, events and global statistics are defined. The following is a part of the preamble that shows some of the declarations of the model. Equation (4.5.1.1) shows the declaration of the TRUCK as process along with GENERATOR and some other processes. In equation (4.5.1.2) truck is defined as a dynamic entity as the trucks are animated in the program.

Preamble

```
processes include GENERATOR, RAMP.TRUCK, ICE.SENSING
  AND MENUPROC, bridge, truck1                               ...(4.5.1.1)
every TRUCK
  has a TRUCK.TYPE
  and a TRUCK.LOCATION
  and a TRUCK.COLOR
  and may belong to the RAMP
  and may belong to the HIGHWAY
every truck1 has a truck.tipe
define ROAD.STATUS, truck.tipe, DISTRIBUTION as a text variable
define TRUCK.TYPE, FELD.ID and STAT as text variables
define CYCLE.TIME, ICE.TIME, TR.S and AVR as real variables
define TRUCK.LOCATION, TRUCK.COLOR and TRUCK.WB
  as integer variables
```

```

define vel.tr,MIN,MAX,thrhold,VELTR, SCALER AS REAL VARIABLE
defineIR,IR1,IR2,IR3,IR4,IR5,MIND,MIN1, MAX1,
MAXD,WT AS REAL VARIABLES
define MENU AS A POINTER variable
define randvar, var, CLOCKTIME AS double variables
display variables include CLOCKTIME, randvar, var
define X, Y AS 1-DIM ARRAY
define s as 1-DIM REAL ARRAY
define YPLOT as double variable
display variables include YPLOT
.
.
dynamic graphic entites include truck (4.5.1.2)
.
.
define .white to mean 1
define .blue to mean 2
.
.
end

```

In the preamble, mode of the variables is undefined initially, so as to make it simpler to assign the mode of any variable in any routine. Graphical entities are defined separately as display variables. Entities which move on the screen are defined as dynamic graphic entities. Different colors used for the graphics screen are also declared in this part of the program. No calculations are allowed in the preamble.

4.5.2 Main

Initialization of the different variables is done in this part of the program. This part of the program, when executed, shows the main window of the graphical interface as shown in the figure 4.6.1a. Depending upon the selection, different parts of the program is executed.

```

Main
call DEVINIT.R("VT, GRAPHIC") yielding DEVICE.ID
open 7 for input, DEVICE = DEVICE.ID
Open 8 for output, DEVICE = DEVICE.ID
use 8 for graphic output
show form with "r1.frm"
let SIM.TIME = 0
let DDVAL.A(DFIELD.F("STM", FORM)) = SIM.TIME
if FIELD.ID = "EXIT"
stop
endif
.
.
if RAMP.FLAG NE 0                                     ...(4.5.2.1)
activate a generator now
endif
.
.
let TIMESCALE.V = SCALER*100/60
let TIMESYNC.V = 'UPDATE.CLOCK'
VXFORM.V = 1
.
.
call SET.DEFAULTS                                     ...(4.5.2.2)
activate a menuproc now
start simulation
end

```

This part of the program start the simulation, sets the ratio of simulation time to real time, sets the graphics screen and calls other routines. Equation (4.5.2.1) shows that if the ramp is selected in the main menu, the generator will be activated and equation (4.5.2.2) call the routine which sets all the default values for the input parameters.

4.5.3 Routine Set.Defaults

This routine sets all the default input values which can be viewed from the graphics windows.

Routine Set.Defaults

```
let MIND = 950
let MAXD = 1250
let DISTRIBUTION = "POISSON"
let ROAD.STATUS = "DRY"
if RAMP1.FLAG ne 0
let RADIUS1 = 105
.
.
If RAMP2.FLAG ne 0
.
let RADIUS2 = 900
.
endif
endif
end.
```

4.5.4 Process Generator

This process generates trucks according to the given distribution at a given frequency. Here, as the time units are selected as seconds, equation (4.5.4.1) shows changing of simulation time from hours to seconds and activating the following loop until the system time variable TIME.V is greater than the given simulation time.

```
Process Generator
until TIME.V >= SIM.TIME * MINUTES.V * SECONDS.V          ...(4.5.4.1)
do
    activate a Truck now
    if DISTRIBUTION = "UNIFORM"
        wait UNIFORM.f(MIND/100, MAXD/100, 1) units
    else
        .
    endif
endif
loop
.
end
```

4.5.5 Process Truck

This is the major component of the program. This process activates almost all of the remaining routines and processes either directly or indirectly. The routine assigns truck type to each truck randomly. Here, to represent the real world conditions, about 80% of all the trucks generated are assigned to be SEMI - TRAILERS. Some of the trucks generated take the ramp and some stay on the highway. As our major concern is about the trucks taking the ramps, more than about 50% of the trucks are assumed to take the ramp. In the equation (4.5.5.1) it is shown that, if we select the first ramp in the main menu, the program will activate the respective module and similarly, the second ramp selection is shown in equation (4.5.5.2)

Process Truck

```
    Let N = Randi.f(1,10000,1)
if N < 2000
    let TRUCK.TYPE(TRUCK) = "S.UNIT"
else if
    N < 9000
let TRUCK.TYPE = "SEMI.TRAILER"
else
let TRUCK.TYPE(TRUCK) = "TRACTOR.TRAILER"
endif
.
.
let K = randi.f(1,10000,2)
if K < 4000
let I = 1
if RAMP.FLAG ne 0
    call move.tr giving TRUCK.TYPE.., I                ...(4.5.5.1)
endif
.
.
else
file this truck in Ramp
suspend
let I = 2
.
.
```

```

if RAMP2.FLAG ne 0
call CIRC.RAMP giving TRUCK.TYPE..., I          ...(4.5.5.2)
.
.
end

```

4.5.6 Routine Move.Tr

This routine is activated from the process truck when the first ramp (Ramp1) is selected in the main graphics window. This program shows the graphical display of Ramp1 (equation 4.5.6.1) and defines the path for the trucks traveling through this section. This routine shows different kinds of trucks using different colors (eqn. 4.5.6.2) and assigns a speed to each of the trucks randomly, according to the given inputs. This is done as shown in equation (4.5.6.3). The direction and speed of the truck are defined through out its path. Trucks staying on highway are assumed to travel at a constant speed throughout the section. Trucks taking the ramp are tested for stability at every 10 ft they travel. Deceleration values are input for each of the ramp curves. The stability of the truck traveling on the ramp is tested by calling the routine Truck.Dyn, as shown in eqn. (4.5.6.4). The routine Truck Dyn decides whether the lateral acceleration value of any truck is exceeding its threshold value and sends a message back to this routine. If the truck's lateral acceleration value exceeds its threshold value, the program beeps and the truck vanishes showing a possible crash. This is done as shown in eqn. (4.5.6.5).

```

Routine MOVE.TR given TYPE, I
Create a road
show road with "colrod2.icn" at (747,595)      ...(4.5.6.1)
if TYPE = "S.UNIT"
    show TRUCK with "TR1.ICN"                  ...(4.5.6.2)
.
.

```

```

let SPEED = uniform.f(MIN, MAX, 1)
let x1 = 0
let x2 = 1500
let y1 = 0
if I = 1
let DIRECTION = arcsin.f(abs.f(x1))
let SPEED = SPEED * 1.47
let velocity.a(TRUCK) = velocity.f(SPEED, DIRECTION)
wait 380/speed units
endif
.
else if = 2
let p = 0
until p =275
do
let vel.tr = sqrt.f(SPEED**2 - 2*A*1.47*25)
let velocity.a(truck) = velocity.f(vel.tr, -pi.c/30)
let orientation.a(Truck) = -pi.c/30
let t = (2*vel.tr+sqrt.f((2*vel.tr)**2 - 8*a*1.47*25))/(2*a*1.47)
wait t units
.
.
.
call ini.icons given type, IR, P1 trstat
add 1 to P1
if trstat = "acc"
create a blow
.
.
let I=7
store I in BEEP
write BEEP as a 1, + using 6
show blow with "blow.icn" at (x,y)
wait 0.05 units
.
let velocity.a(Truck) = 0
erase Truck
suspend
.
.
.
end

```

...(4.5.6.3)

...(4.5.6.4)

...(4.5.6.5)

4.5.7 Routine Circ.Ramp

This routine is similar to the routine Move.Tr except that this routine represents the calculations involved for the second ramp. The main difference between these two routines are the default values of the parameters, the paths and velocities of the trucks. This routine also checks for the stability of the trucks exiting from the second ramp, at every 10 ft they travel, by activating the routine Truck.Dyn.

Routine Circ.Ramp given type, I

```
.  
.
let vxform.v = 1
create a road
show road with "colchk.icn" at (760, 595)
.
.
let motion.a(Truck) = 'linear.r'
if I = 1
let location.a(Truck) = location.f(100,698)
let velocity.a(truck) = velocity.f(speed, direction)
.
.
call ini.icons given type, IR, P1 yielding trstat
if trstat = "acc"
.
.
let velocity.a(truck) = 0
erase truck
suspend
.
.
end
```

4.5.8 Routine Chinn.Ramp

This routine represents the simulation of the third ramp of the program. This routine differs from the above two routines only in the default values of the input parameters, directions and velocities of the trucks. Once executed, this routine shows the third ramp on the graphical screen and simulates the system according to the prevailing conditions.

4.5.9 Routine Truck.Dyn

This routine is called from all the three ramp modules and it decides whether a truck's lateral acceleration is exceeding the threshold value. If so, this routine returns a message to the ramp module, causing the program to beep and make the truck disappear from the graphical screen. Depending upon the type of the truck, as shown in equation (4.5.9.1), this routine assigns a weight to the truck and according to the weight, it assigns a pay load height (eqn. (4.5.9.2)) and hence determines the threshold value for the truck randomly (eqn. (4.5.9.3)). The value of superelevation is then added to the threshold value. Now the program calculates the lateral acceleration of the trucks and compares the value with the above value (eqn. (4.5.9.4)). If the lateral acceleration value exceeds the effective threshold value, then the program reports an accident. Otherwise, the program checks if the lateral acceleration is greater than the summation of superelevation and the friction factor value (eqn. (4.5.9.5)) and decides whether there is a crash.

```
Routine Truck.Dyn given TYPE, IR, P1 yielding TRSTAT
if P1 = 0
if type = "s.unit"
let wt = uniform.f(34000,48000,1)
let h = uniform.f(75, 85.5, 1)
else if type = "semi.trailer"
```

```

let wt = uniform.f(75000,85000,1)           ...(4.5.9.1)
let h =uniform.f(83.5,100,1)               ...(4.5.9.2)
.
.
if h > 80
if h < 84
let thrhold = uniform.f(0.34,0.36,1)
else
if h < 89
let thrhold = uniform.f(0.3, 0.34, 1)       ...(4.5.9.3)
else
.
.
let thrhold = uniform.f(0.24, 0.255, 1)
endif
.
.
let thrhold = thrhold + se
let e = vel.tr**2/(IR*32.3)
if ROAD.STATUS = "DRY"
if e > thrhold                               ...(4.5.9.4)
let trstat = "acc"
endif
if ROAD.STATUS ne "DRY"
activate a Ice.Sensing now
if e > frict.fact + se                       ....(4.5.9.5)
let trstat = "acc"
endif
let G = grade.ramp
if e > (frict.fact + g)
let trstat = "acc"
endif
.
.
end

```

4.6 Description of the graphic display

The graphical interface is developed using SIMGRAPHICS to make the program easier to understand. Once the program is executed, the main window, as shown in figure 4.6.1a, is seen on the screen. Here the user needs to make a selection of the ramp and the simulation time has to be entered. This can only be done by using the mouse. After making the selection and clicking on the O.K. button the window with the selected ramp is seen. This window is shown in figure 4.6.1b. To make it simpler, different kinds of trucks are assigned different colors. Single unit trucks are shown in yellow, semi - trailers are shown in green and the tractor trailers are shown using red color.

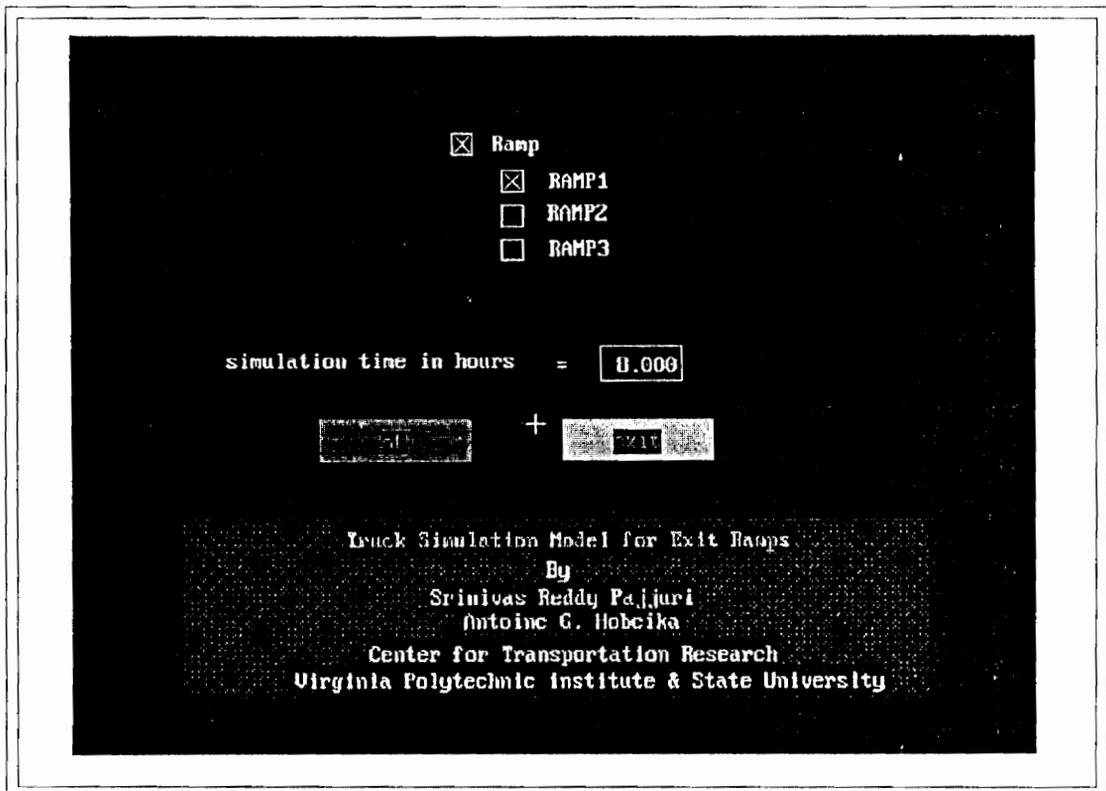


Figure 4.6.1a: Main window of the graphical display

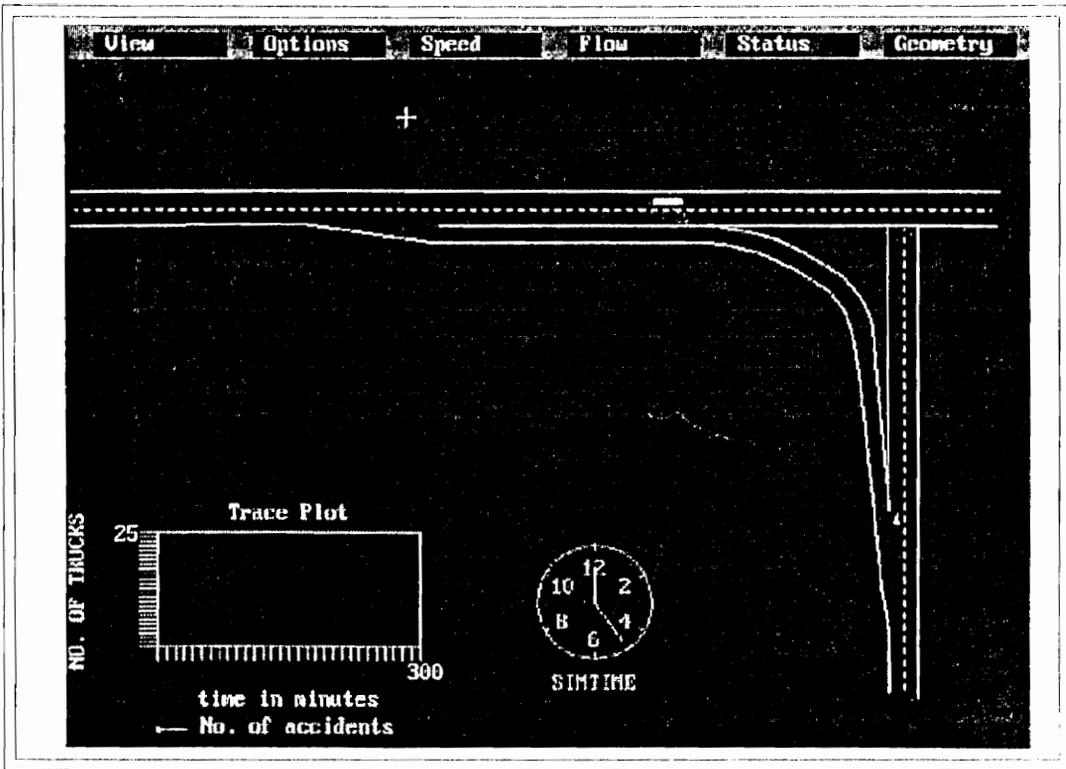


Figure 4.6.1b: Graphical window showing the first ramp

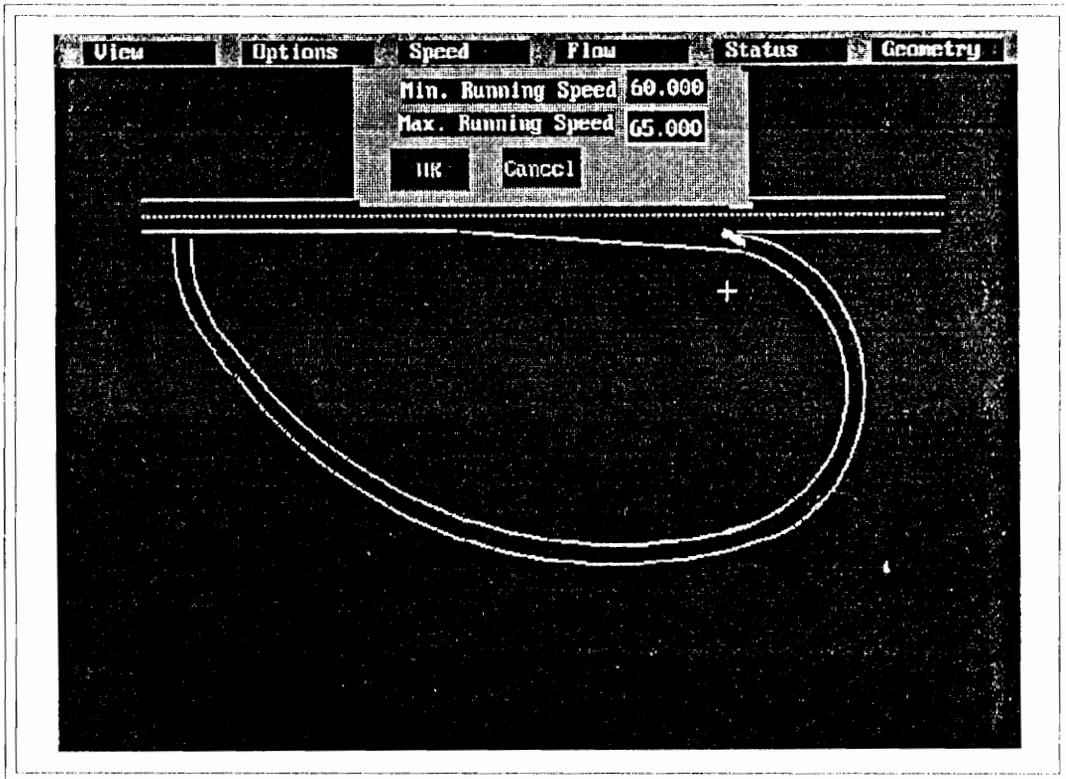


Figure 4.6.1c: Graphical window showing the Speed menu for second ramp

The trucks are generated at the left end of the graphics screen and they travel from left to right. For the first two ramps the graphics screen represents a section of about 1500 ft. and for the third ramp, a section of about 2000 ft. is represented. Input parameters can be changed using the menubar, any time during the simulation. For example the speed of the traffic can be changed by clicking on the "Speed" menu as shown in figure 4.6.1c. When the mouse is clicked on any of these menus, default values allocated for that particular ramp are shown in the menu window.

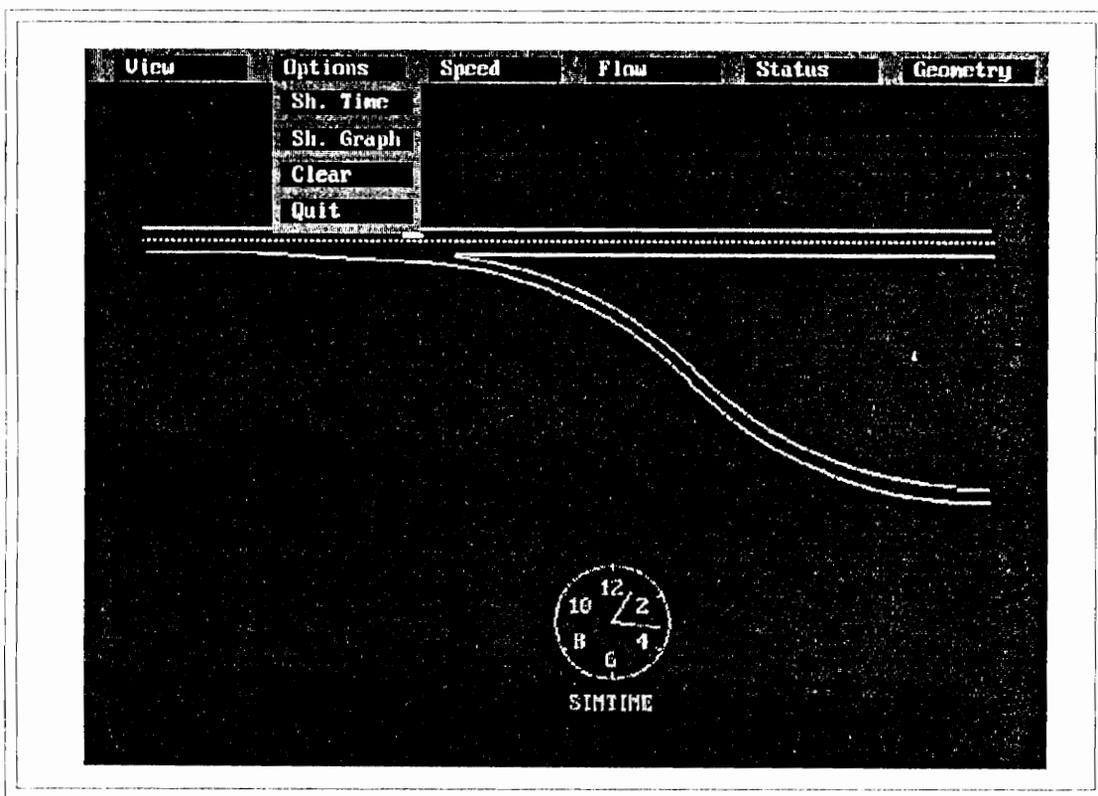


Figure 4.6.1.1: Graphical window showing the Options Menu for third ramp

4.6.1 Menubar description

The menubar in this program consists of six main menu functions and each of them has some sub-functions. The menu functions are briefly described below:

1. View

This function changes the background color according to the convenience of the user. The background can be changed into four different colors namely blue, red, green and none. The default screen color is light green.

2. Options

This function menu has three sub - functions associated with it. "Sh.Time" function displays the simulation time on the screen in a clock format, "Sh.Graph" function displays a graph, showing the number trucks taking the ramp and the no. of possible crashes versus time. The quit function terminates the program. The window executing this function is shown in figure 4.6.1.1.

3. Speed

This function helps the user to change the speed of the traffic flow during the simulation. The speed is specified in lower and upper limit format with mph as the units. This window can be seen in figure 4.6.1c. Once the speeds are changed the "O.K." button has to be clicked in order to make the changes effective. The program will terminate if the upper limit is set to zero or if the upper limit is set lower than the lower limit.

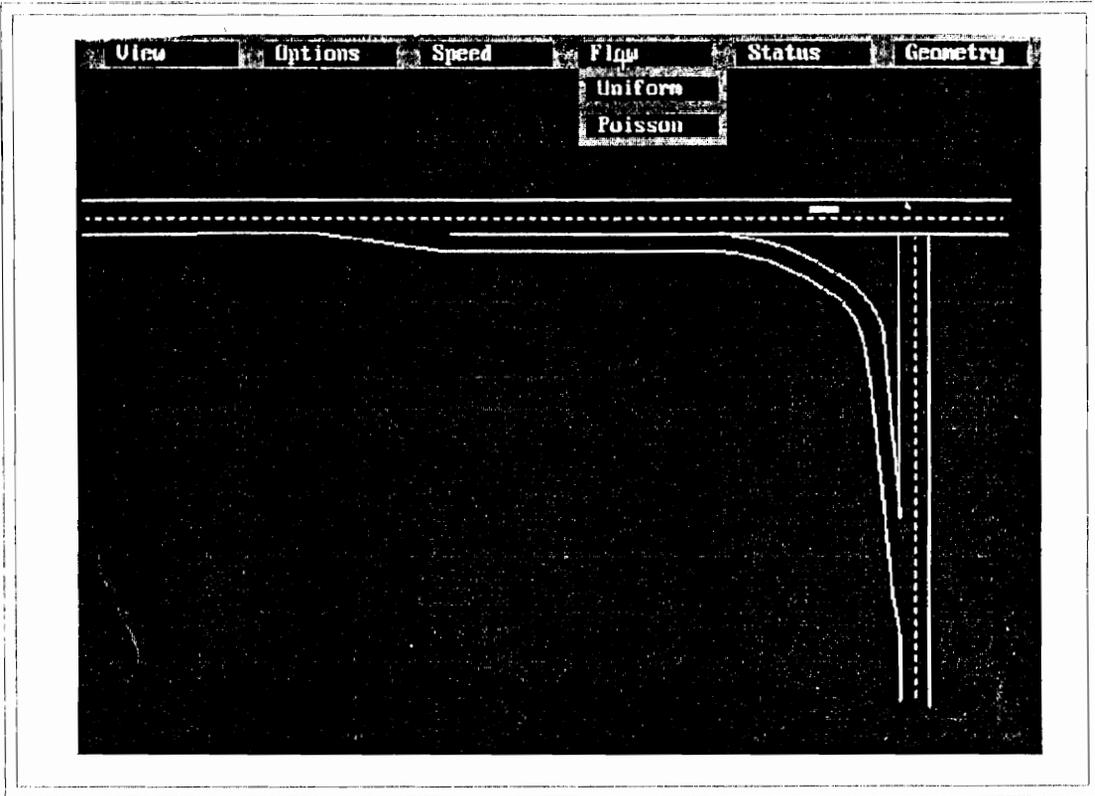


Figure 4.6.1.2: Graphical window showing the Flow Menu

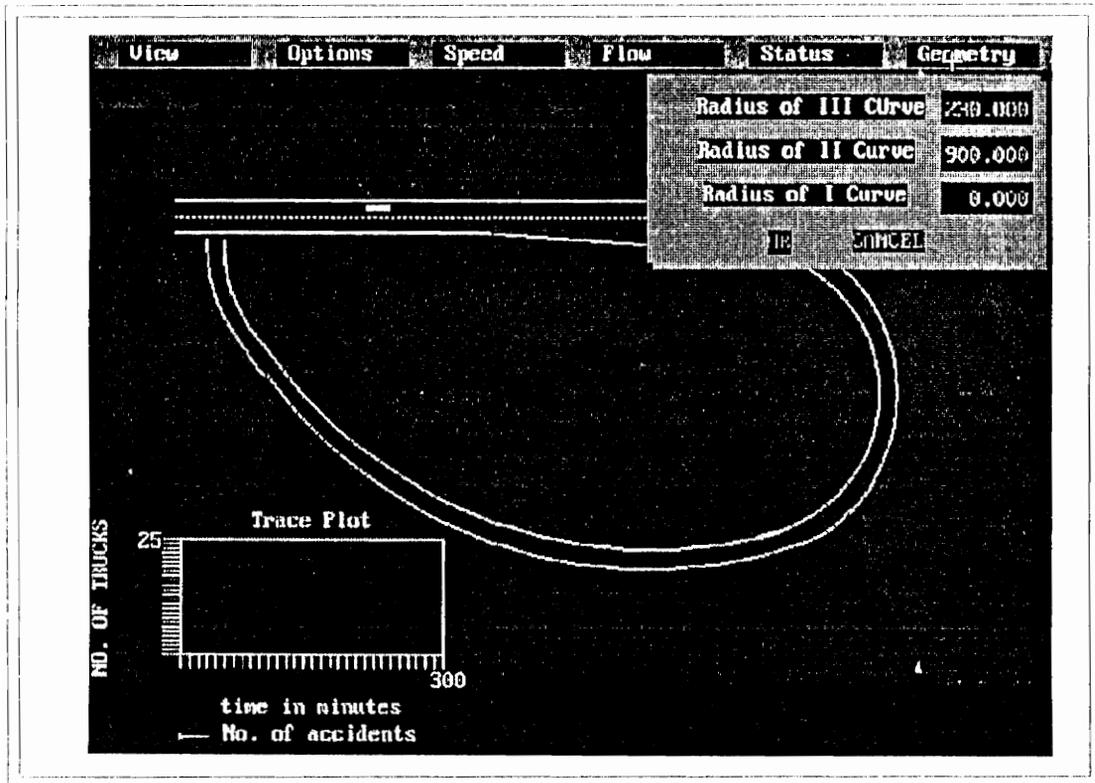


Figure 4.6.1.3: Graphical window showing the Geometry Menu

4. Flow

This function sets the distribution of truck arrivals. Only two distributions, poisson and uniform, are considered for this program. The frequency can also be changed any time. The default is set to poisson with a frequency of about 200 trucks per hour. Window for this function is shown in figure 4.6.1.2.

5. Status

This function helps change the status of the pavement. The status can be dry, wet and icy. The default status of the pavement is dry. The program changes the friction factor values depending up on the given condition, according to the AASHTO recommendations.

6. Geometry

This functions changes the radii of the ramp curves during the simulation. The first ramp consists of three curves and the remaining ramps consist of only two ramps. When these ramp programs are executed, the radius of the third curve is shown as zero. Default values are shown in these windows (figure 4.6.1.3) depending on the selected program execution. The program will terminate if one of the radii is set to zero.

6. Default functions of the program

Apart from the functions mentioned above, the program has some in-built default functions, which show the crash speed of the truck on the screen, show the crash graphically, and make the computer beep when there is a possible crash.

5.0 MODEL VALIDATION

As mentioned earlier the model represents two existing ramps, ramp2 and ramp3, where rollover accidents were reported in the past. The accident on ramp2 occurred during the wet surface conditions and it involved a tractor-semitrailer. The major defect of this ramp was the length of deceleration lane, which is not sufficient to allow the heavy trucks to reduce their speeds to the safe speed limit on the ramp. The accident was reported at the beginning of the first curve as shown in figure 5.1.1. The accident occurred eventhough the truck was traveling at the post speed limit of 30 mph. The posted speed limits do not provide enough factor of safety for heavy trucks especially when the surface is not dry.

The results of the model for ramp2 also confirm the fact the factor of safety provided for heavy trucks is not sufficient. For an average running speed range of 50 - 60 mph on the highway, heavy vehicles with weaker deceleration capabilities may not be able to reduce their speeds to less than 30 mph when they reach the critical curve of the ramp. Some of the accident locations obtained from the model calibration are shown in figure 5.1.2 which shows that the probability of an accident occurring at the beginning of the curve is higher than any other location on the curve. The model results also show that about 85% of the total number accidents taking place are those involving tractor-semitrailers . Because of their lower rollover thresholds, semi-trailers are exposed to rollover crashes more than any other type of trucks. The location of the accident, for most of the accidents predicted by the model, is the beginning

of the critical curve i.e. the curve with 230 ft radius, which is also the location for an actual rollover.

Two rollover accidents, both of them during the dry surface conditions, were reported in the past on ramp3. One of them was reported at the beginning of the first curve and the other was reported at the beginning of the second curve of this reverse curved ramp as shown in the figure 5.1.3. As the radii of these curves are high, drivers tend to exceed the speed limits without having any knowledge about the change in the curvature. The posted speed limit of on this ramp is 35 mph. In one of the accidents reported, the truck was traveling at a speed of 50 mph and it turned over at the beginning of the first curve. The other accident, which was reported at the beginning of the second curve of the ramp, was reported at a speed of 35 mph. Tractor trailer was involved in one accident and a semi-trailer was involved in the other one.

The model predicts no crashes for an average running speed range of 50 - 55 mph and 6 crashes for the range of 55 - 60 mph in a 12 hr. period. Almost all of these accidents are predicted either at the beginning of the first curve or at the beginning of the second curve as shown in figure 5.1.4. Out of these 6, 5 were predicted to be semi-trailers and 1, to be a tractor trailer. The model did not predict any accidents involving single unit trucks in a 12 hour period during the dry surface conditions. This can be attributed to the high radii of the ramp curves. Though the speed limit is 35 mph, the ramp has a high factor of safety for trucks because of its geometry. The model allows some of the trucks to travel at about 45 mph without crashing. But the speed at the beginning of the second curve is critical because of a change in the direction. Almost 90% of the accidents with speeds at about 35 mph were reported at this location.

As the model only follows certain conditions and rules, it tends to predict a higher number of accidents for certain conditions. As it is not possible to input the human factors and driver skills affecting an accidents, the model predicts all the accidents that would have been avoided with the skills of an experienced driver. This is the reason why the model not only predicts accidents for the exact conditions under which real accidents took place, but also estimates the number of accidents to be higher than the actual number for similar environment. The accident locations predicted for the first ramp are shown in figure 5.1.5.

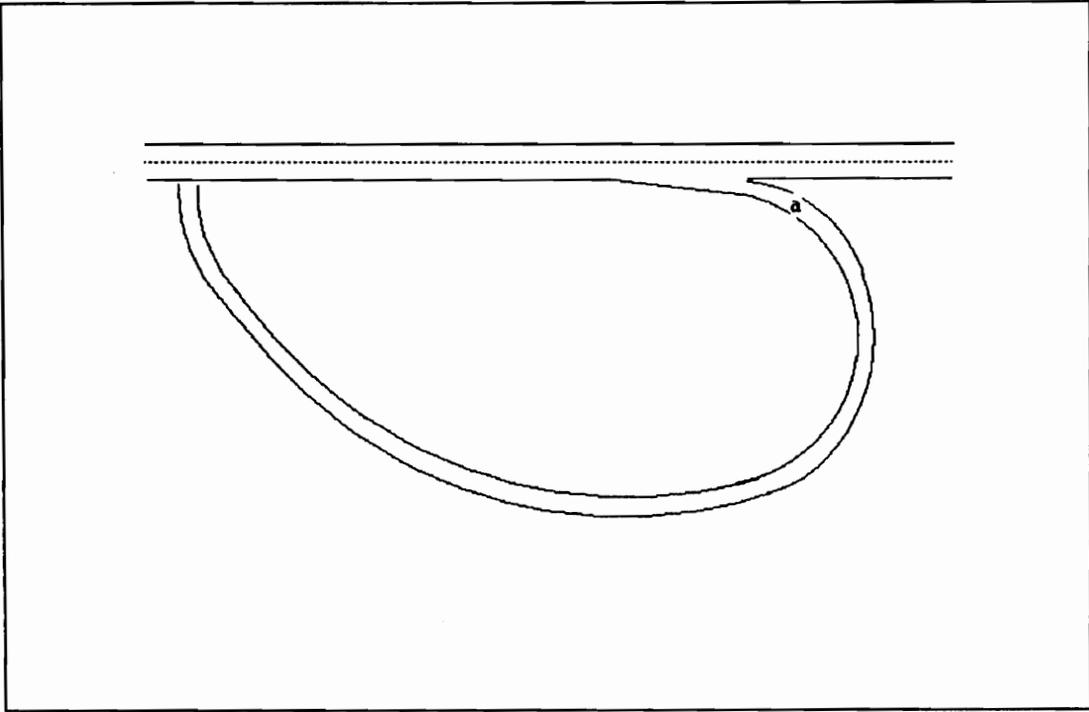


Figure 5.1.1: Actual accident location on Ramp2

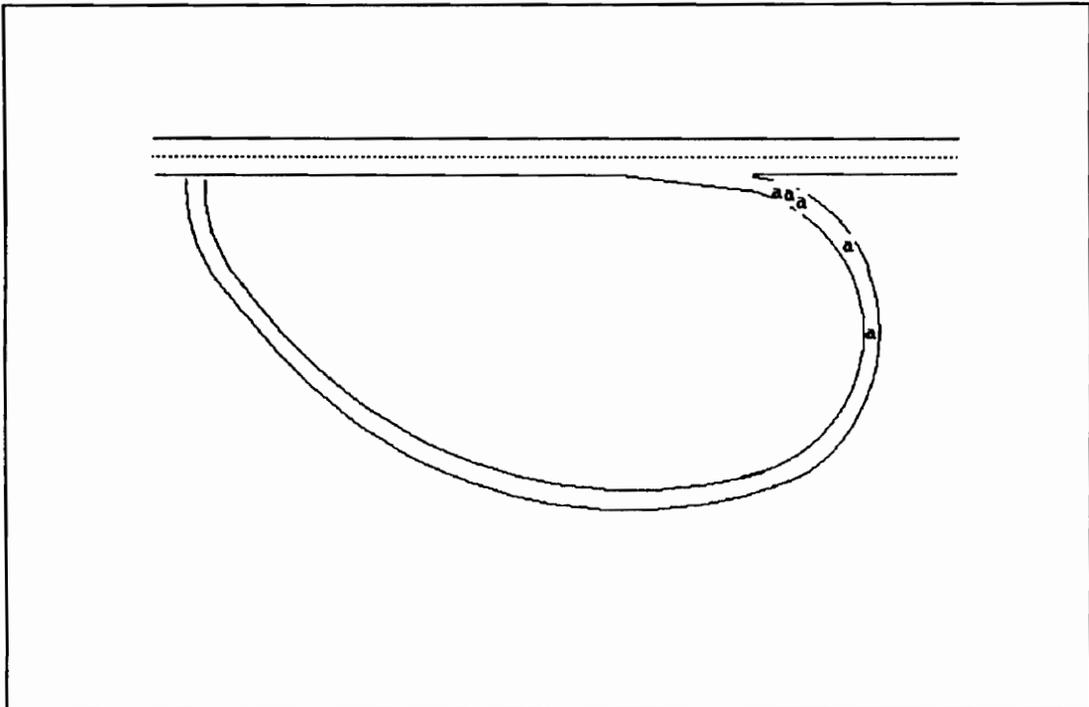


Figure 5.1.2: Accident locations predicted by the model for Ramp2

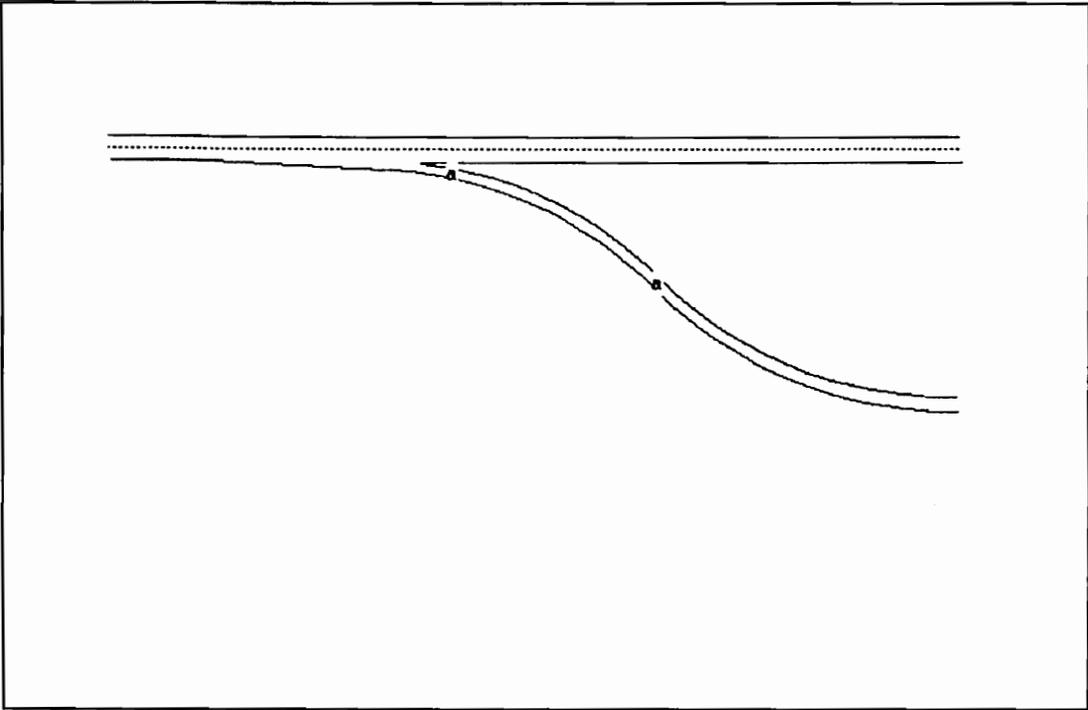


Figure 5.1.3: Actual accident locations on Ramp3

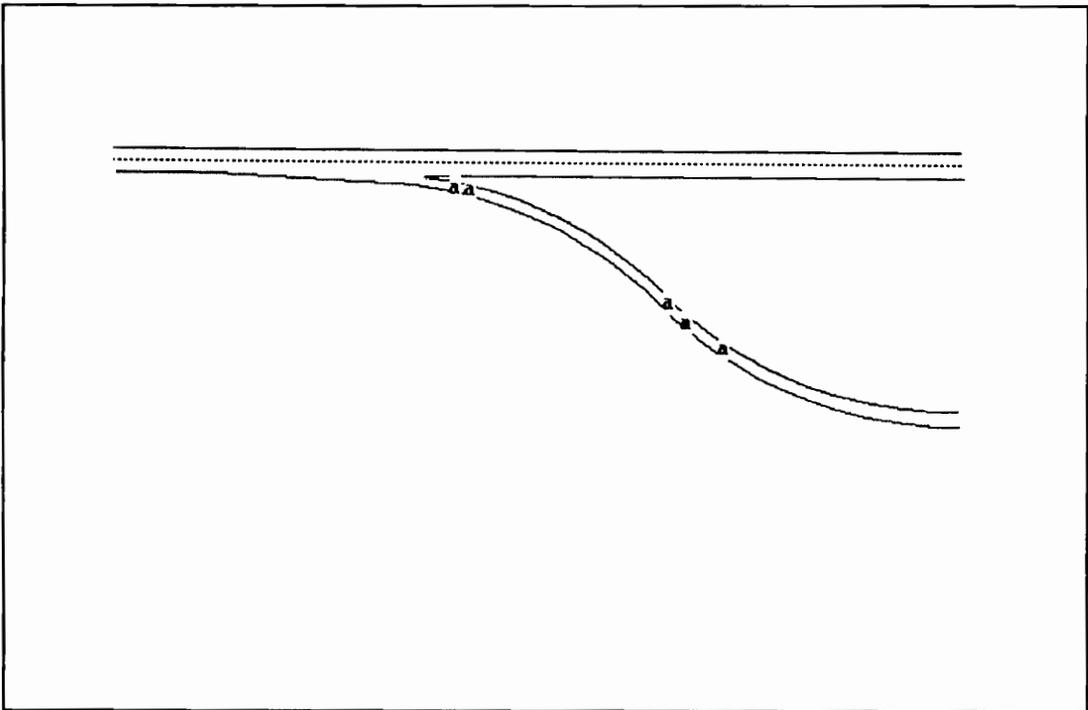


Figure 5.1.4: Accident locations predicted by the model for Ramp3

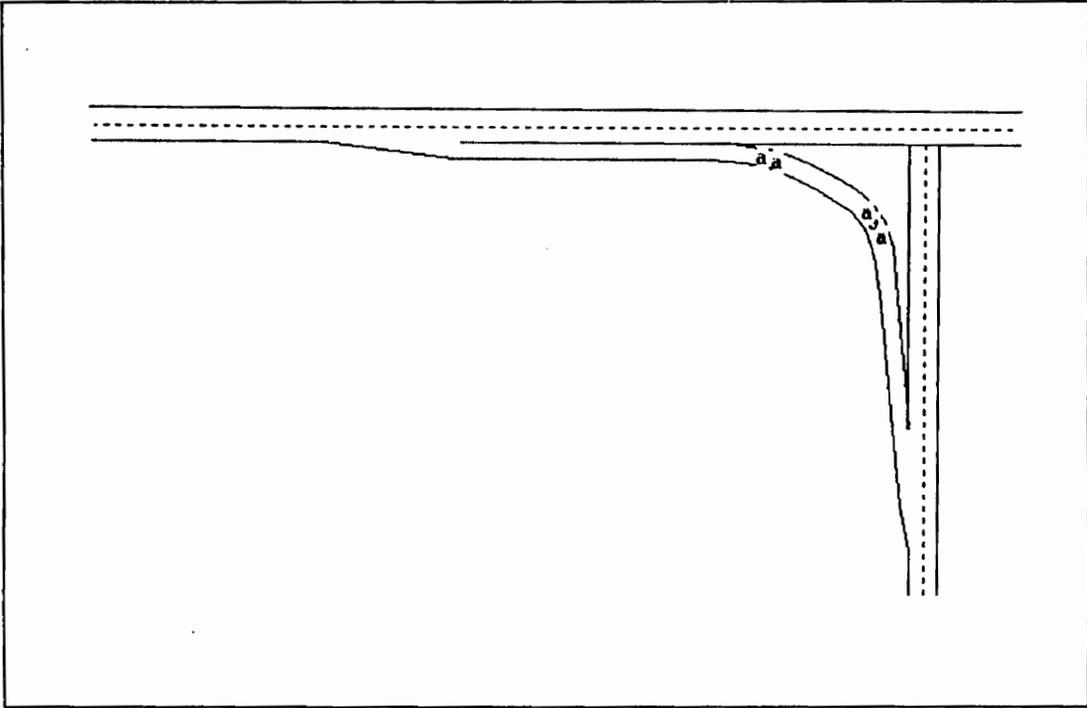


Figure 5.1.5: Accident locations predicted by the model for Ramp1

6.0 MODEL RESULTS AND ANALYSIS

As the main goal of this research is to test the model for different weather and geometric conditions of the highway, sensitivity analysis is done for the three ramps mentioned in the study. The model for each ramp is tested for changes in the surface conditions, ave. highway speeds and the radii of the critical curves affecting the safety of trucks. The results are analyzed below:

6.1 Ramp1

As mentioned earlier, ramp1 is a compounded curved ramp consisting of three curves. This ramp is designed according the AASHTO design standards. The model is run for a 12 hour period to make the results more accurate and dependable. Of all the trucks generated, about 20% of them are assumed to take the exit ramp. First of all, the model is tested for different surface conditions, with constant average running speed. Figure 6.1.1 shows the results for three different surface conditions at an average running speed range of 50 - 55 mph on the highway.

The model generated 524 single unit trucks, 1635 tractor-semitrailers, and 259 tractor-trailers in a 12 hour period. Out of 465 trucks taking the exit ramp, the possible no. of rollovers is about 1.2% for an average running speed of 50 - 55 mph on the highway. 3% of possible accidents were reported by the model during the wet weather conditions and about 6.5% crashes were reported for icy surface conditions when the average running speed is constant. A sensitivity

analysis is done by changing the average running speed for three different surface conditions.

For the dry surface condition, as shown in figure 6.1.2, for a speed range of 45 - 50 mph, about 0.43% possible crashes were reported and for a speed range of 55 - 60 mph, the percentage of possible crashes was 2.8%. A similar analysis done for wet surface conditions, as shown in figure 6.1.3, predicted the possible crashes to be 4.3% for an average running speed range of 55 - 60 mph and only 0.7% for the speed range of 40 -45 mph. For the icy surface conditions, as shown in figure 6.1.4, the model predicted 6.5 % crashes for a speed range of 50 - 55 mph and the number was reduced to 1.2% when the speed range was 40 - 45 mph.

The critical curve in the first ramp of the model is the one with the smallest radius i.e., 105 ft. The radius of this curve is increased by 10 to 15 percent to test the sensitivity of this curve radius. The model, which had predicted 2.8% possible rollovers for a speed range of 55 - 60 mph, predicted 1.9% crashes for a 10% increase in the radius and 1.3% crashes for a 15% increase. A plot of these values is shown in the figure 6.1.5.

6.2 Ramp2

An analysis, similar to the one for ramp1, is done for ramp2 to test the ramp for different surface and geometric conditions. Figure 6.1.1 shows the analysis for different conditions at a constant average speed range of 50 - 55 mph. For dry conditions, out of 465 trucks taking the ramp, model predicted 1.5% possible crashes and for wet and icy conditions the possible crashes are 4.9% & 7.3% respectively.

For changes in the average running speeds on the highway during the dry surface conditions, the model responded as shown in figure 6.1.2, which shows 0, 1.5, and 2.9 percent possible crashes for the speed ranges of 45 - 50 mph, 50 - 55 mph, and 55 - 60 mph respectively. In a similar analysis done for the wet surface conditions, as shown in figure 6.1.3, the model predicted 0.21, 4.9, and 6.4 percent crashes for the speed ranges of 45 - 50 mph, 50 - 55 mph, and 55 - 60 mph respectively. The analysis done for icy surface conditions predicted 0.4% crashes for the speed range of 40 - 45, 3.8% possible crashes for the speed range of 45 - 50 mph and 7.3% crashes for 50 - 55 mph speed range.

Ramp2 consists of two curves, with the critical curve having a radius of 230 ft. To test the sensitivity of the ramp geometry, the model is also tested for the changes in the radius of the critical curve. Figure 6.1.5 shows the predictions of the model for increases in the radius of critical curve. Unlike the critical curve of first ramp, this curve has bigger radii and lesser safe speed limit and the model tested for 10 and 15 percent increases in the radius of the critical curve shows considerable reduction in the percent of possible crashes.

6.3 Ramp3

Ramp3 is a reverse curved ramp with two curves of equal radius. As the radii of these ramps are large (700 ft each), drivers tend to speed up without having any knowledge of the reverse curvature ahead. The model is analyzed for different surface conditions and the results are shown in figure 6.1.1. The percentage of possible crashes are very low for dry surface conditions. During the wet and icy surface conditions, the model predicted 2.7% and 6.1% possible crashes respectively for an average running speed range of 50 - 55 mph on the highway.

Analysis done for speed changes shows only 1.29% accidents for the speed range of 55 - 60 mph during the dry surface conditions for the entire 12 hour period. During the wet surface conditions, the predictions are 0, 2.7, & 4.8 percent of possible crashes for the speed ranges of 45 - 50 mph, 50 -55 mph, and 55 - 60 mph respectively. Icy surface conditions resulted in 0.21% possible crashes for the speed range 40 - 45 mph, 2.9% for 45 - 50 mph, and 6.1% possible crashes for the speed range of 50 - 55 mph.

As the critical radius of the ramp is very high, the sensitivity analysis for the changes in the radii shows that for a 15% increase in the critical radius, the percentage might be 0. This may not always be true as the drivers tend to move faster if the curvature is not very high.

Analysis of Ramp1, Ramp2, and Ramp3 for different Surface Conditions (constant ave. running speed (50 - 55 mph))

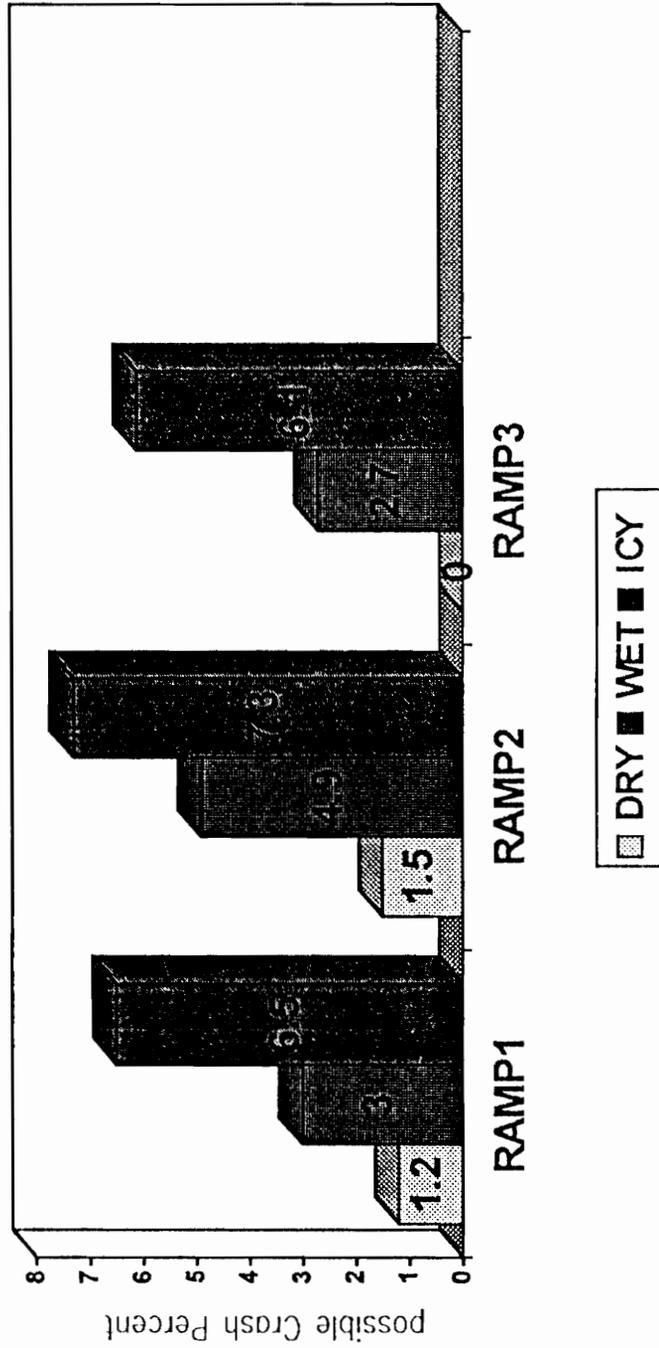


Figure: 6.1.1: Percentage of possible crashes on Ramp1, Ramp2, and Ramp3 on different surface conditions

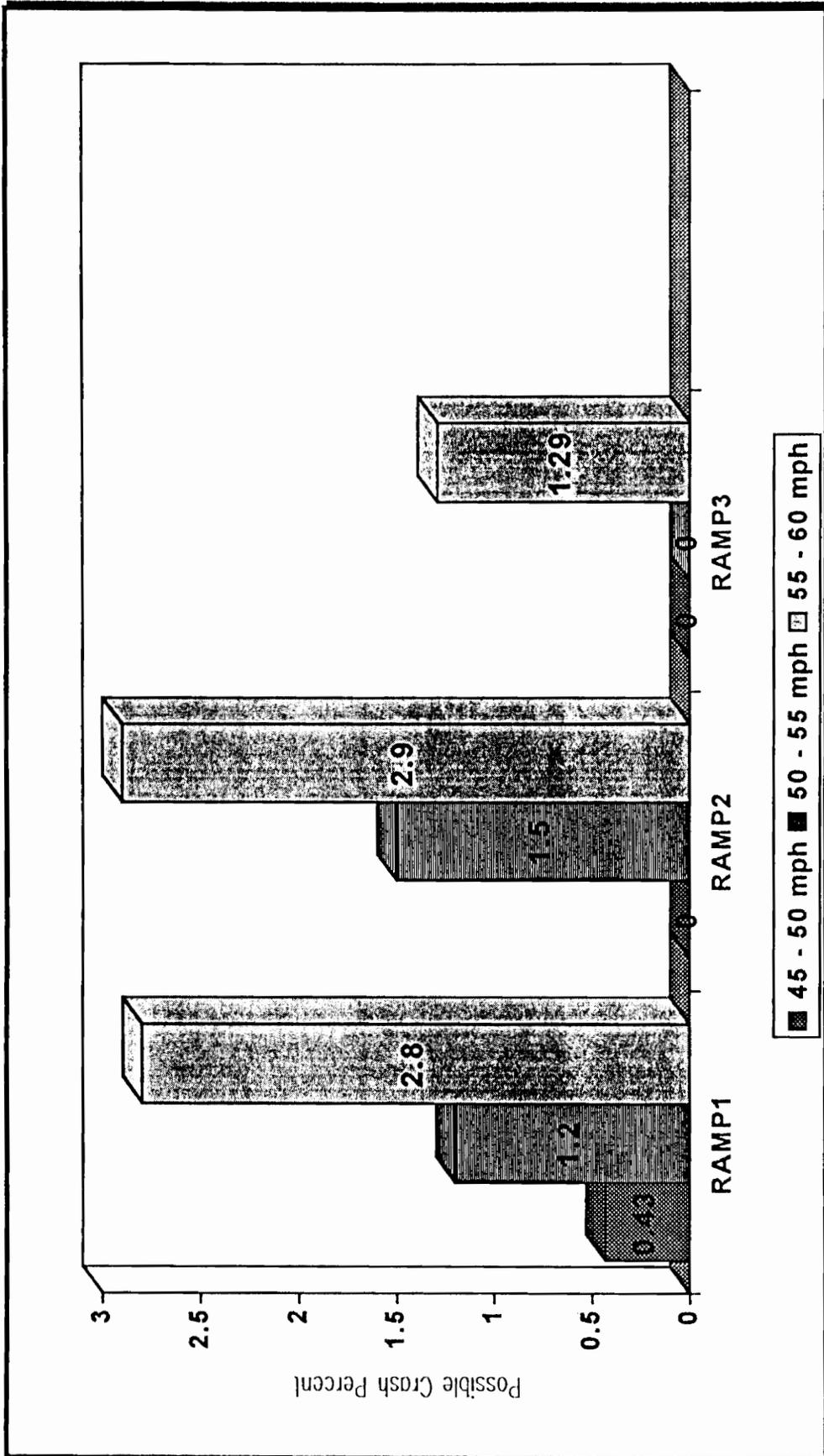


Figure 6.1.2: Model analysis for dry surface conditions

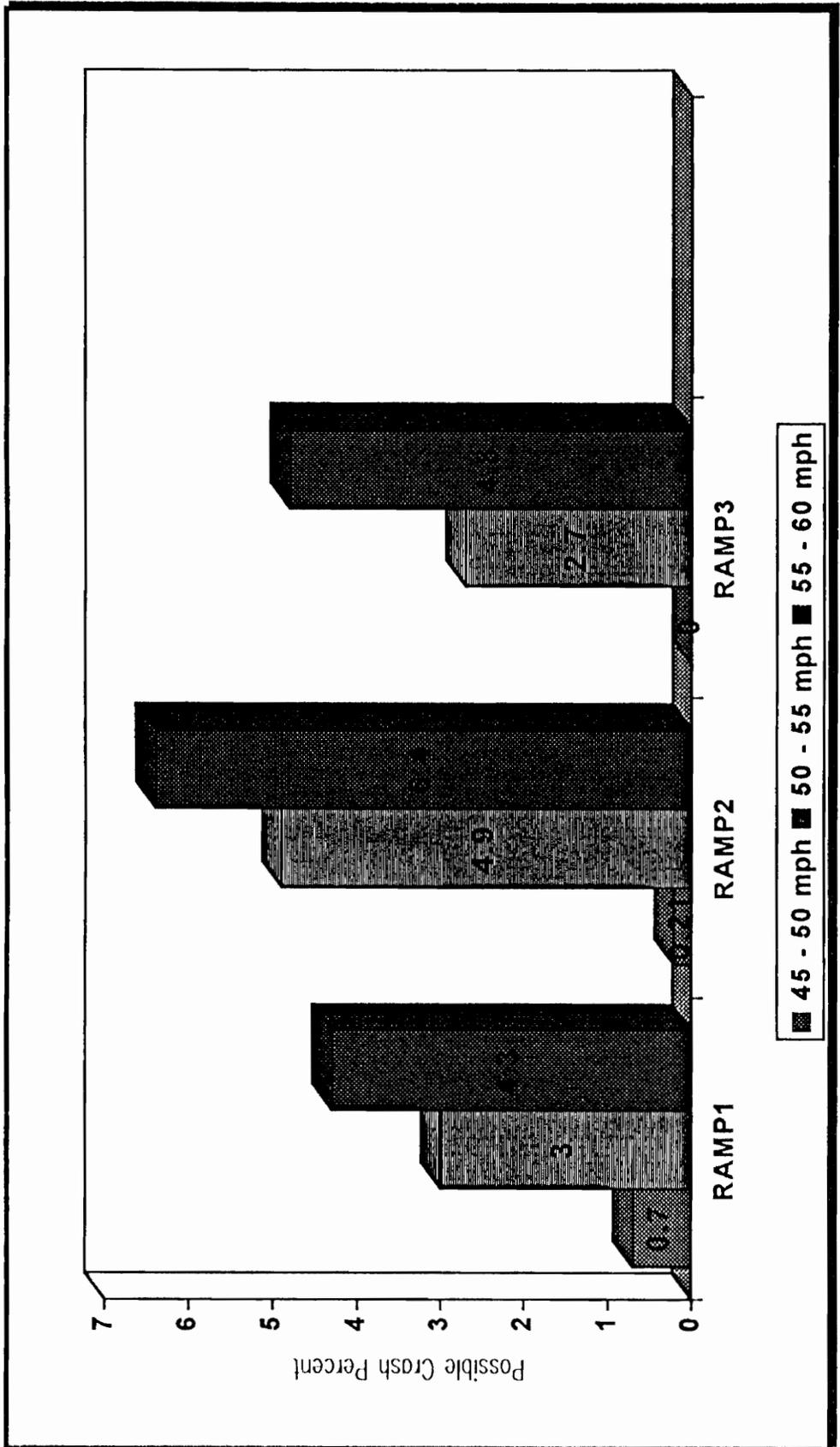


Figure 6.1.3: Model analysis for wet surface conditions

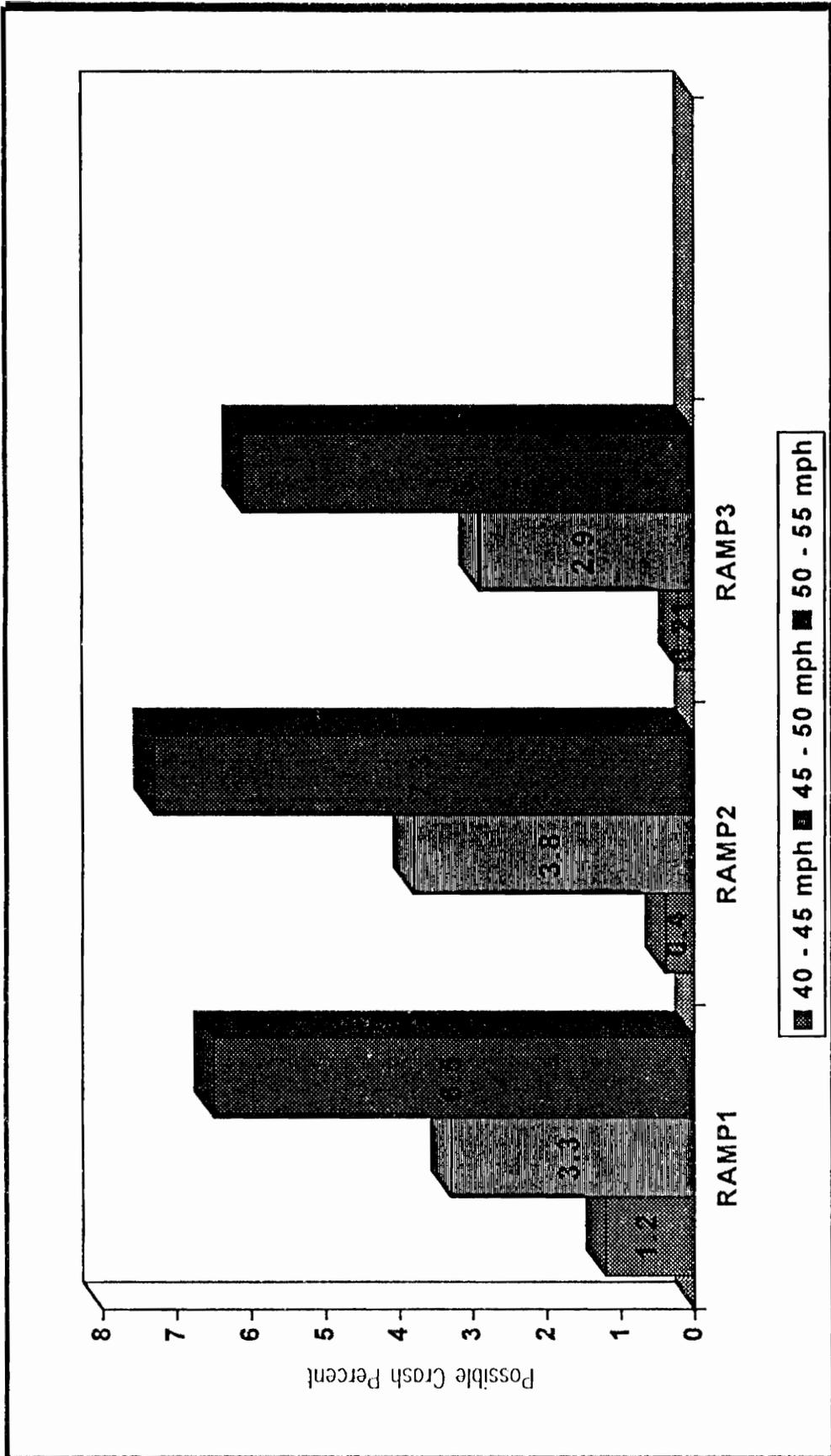


Figure 6.1.4: Model analysis for icy surface conditions

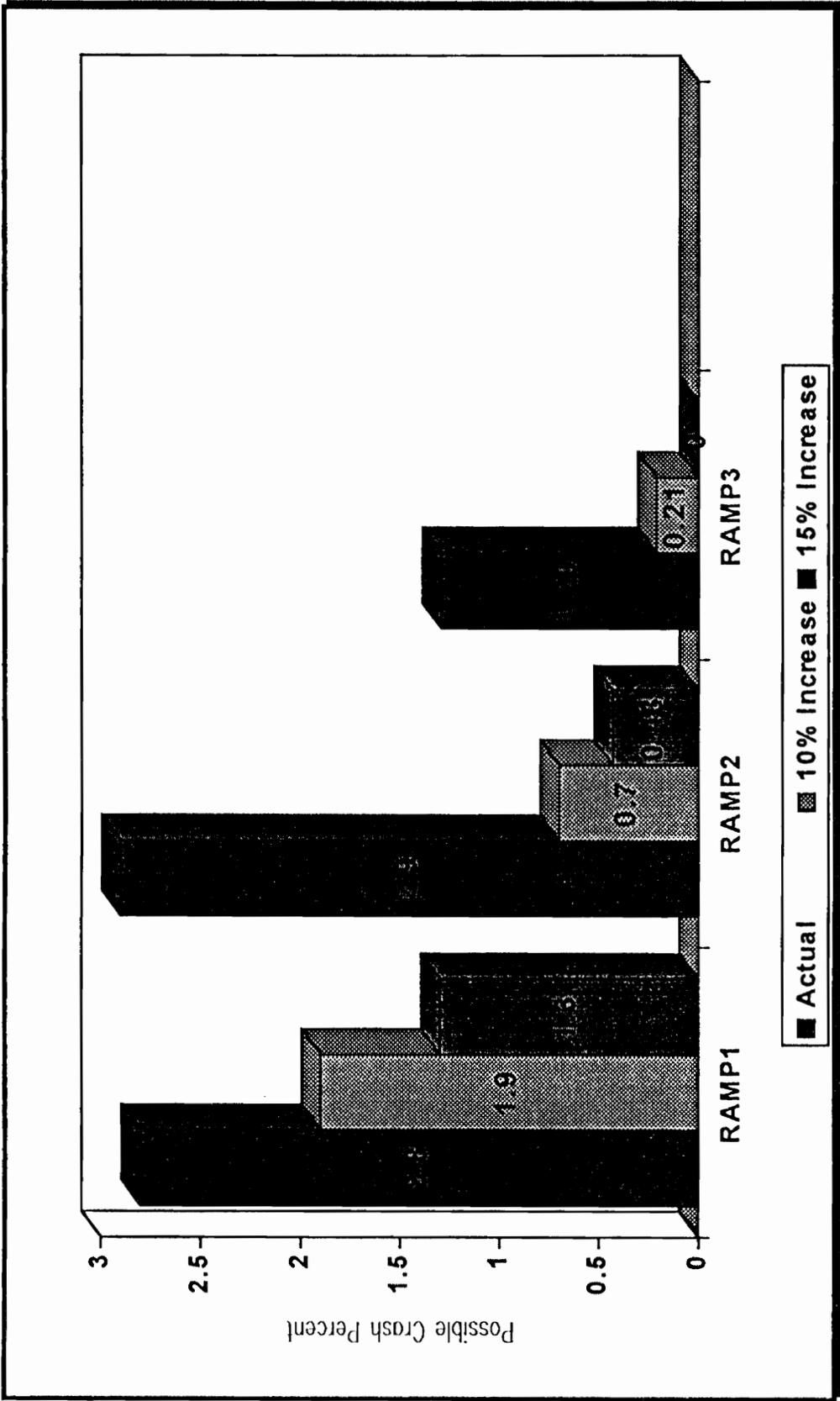


Figure 6.1.5: Sensitivity analysis for critical curve radii

7.0 CONCLUSIONS AND RECOMMENDATIONS

Simulation approach to predict the truck accidents and to analyze the sensitivity of different factors affecting the safety of the trucks has proven to be effective. The model showed that trucks are more exposed to accidents during the adverse surface conditions. The study also estimates higher number of crashes when the surface is not dry and there is no change in the speeds of the trucks traveling on ramp compared to dry surface speeds. It can be concluded that the posted speed limits may not be suitable for heavy trucks especially, when the surface conditions are not dry.

For different surface conditions, the model's prediction of number crashes goes down rapidly (more than 50%) with every 5 mph reduction in the average running speed. This shows that the factor of safety provided for the heavy trucks may not be sufficient. As most of the trucks are involved in crashes at the beginning of a critical curve, it may be concluded that transition to the superelevation is also a major factor affecting the safety of heavy trucks. During the wet surface conditions for example, the results of ramp2 show that a 5 - 10 mph reduction in the average running speeds of the trucks reduces the number of accidents by about 40 to 90%. It can be concluded here that, during the wet and icy surface conditions, the safe speed limit is atleast 5 - 10 mph less than the posted speed limit on the highway. The results from ramp3 show that even the ramp with high radius curves and sufficient factor of safety may not be safe

as the drivers often exceed the safe speed limits without having any knowledge of the sudden changes in the curvature.

The model results also show that tractor semi-trailers are much more exposed to rollover crashes than any other kind of trucks due to its high payload height and suspension characteristics. The model also showed that for a 5 - 10% increase in the radius of the critical curve, there is a considerable reduction in the number of crashes. Results from ramp2 show that for a 10% increase in the radius of the critical curve, the number crashes can be reduced from 2.9% to about 0.5%. This may not always be true as the drivers tend to move faster when the curvature is not very high and tend to exceed safe speed limits more often.

7.1 Recommendations for Future Research

It might be recommended that a more number of existing ramps where accidents were reported in the past should be tested. The effect of the passenger car traffic on the truck speeds may be included in the model to make it more realistic. As the improvements in the geometry of ramps alone may not effectively reduce the number of accidents, the applications of advances information technologies to better inform the drivers about the conditions a head needs to be studied in order to improve the safety of the trucks. Other recommendations might be the study of the driver behavior and human factors.

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